Fatigue Damage Evaluation by Use of "Smart Sensors"

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ABSTRACT

There is a need for an improvement in accuracy of forecasting of residual service life of commercially available aircraft components. Therefore, easy in use and precise non-destructive testing (NDT) methods for determination of the material fatigue are especially attractive. A basic understanding of structural changes during the fatigue damage process on different scaling levels is given by the physical Mesomechanics derived for a medium with local structure. The approach is based on the knowledge of the development of deformation structures (mesostructures) at three levels at the sample surface, micro/meso/macro-structure level, with increasing mechanical cyclic loading. The experiments for NDT detection of deformation structure were performed at AA2024 samples, which had special thin Al- single crystal films, the so-called "smart sensor" glued to their surfaces. For deformation structure detection the topography imaging microscopy and eddy current (EC) detection approach was used with the potential to transition this inspection to an aircraft for an in-situ solution for Structural Health Monitoring (SHM). Results of these investigations will be presented in the present contribution.

INRODUCTION

For the increase the accuracy of commercial component monitors for the forecast the residual duration of life, used today non-destructive testing methods, which determine material fatigue simply and exactly. There are many non-destructive technologies (NDT) which involve the instant inspection of structures for cracks or flaws, without long term monitoring of accumulated damage. At the same time, the real-time techniques are available which monitor structures for cracks or flaws instantly and over a long period of time. Some of these are based on the multi-scaling analysis of damaged materials and sensors. The overall objective is to demonstrate the

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new innovative approach to Structural Health Monitoring (SHM) within the production and maintenance/servicing aircraft industry. The approach is based on the real-time multi-scale monitoring of the smart-designed multilayer thin film sensors (“multi-scale smart skin”) of fatigue damage with the standard electrical input/output interfaces which can be connected to the embedded and on-board aircraft computers [1].

First experiments have brought the evolution of single crystalline Al thin plates under the constrained cyclic mechanical tension [2]. The plate surface undergoes the sharp transition from initially solid flat state to the band-like surface pattern, and then to the more pronounced labyrinth-like bulk structure. These complicated substructure transformations were laid in the basis of the sensors of mechanical damage [3]. More exact investigations of the Al plates under constrained cyclic mechanical tension demonstrate the extrusions, which evolve from random arrangements to regular 2D solid rectangular grid (“Tweed”), and 3D porous rhombic grid of voids (“pullover”)[4]. The previous studies have shown that the both pattern have the apparent fractal behaviour [5].

The IZFP Dresden has realised many experiments for the computation of the fractal dimension from optical images of the topography for evaluation of damaged state of material. The methodical works show that the fractal dimension D_F this images obtains reliable information about of the deformation structure. The parameter D_F increases during fatigue load and exhibits the well pronounced plateaus. The individual plateaus of the fractal dimension together with the absolute value of D_F characterise the level of deformation structure, namely the first plateau is the micro, the second plateau is the meso I and the third plateau is the meso-II-level [6].

The analogical D_F curve dependency from the number of cycles was founded by evaluation of magnetic time-dependent signals of the deformation structure [7]. In this case the one dimensional Barkhausen noise (BN) time series detects very well the fatigued deformation structure. The evaluation of BN by fractal analysis was used successful for fatigue damage evaluation.

In this paper we will characterised the damaged state of the bulk material by the use already known algorithm of Gaussian smoothing for the evaluation of optical images of topography of “smart sensors”. In the case non-ferromagnetic metal (Al) the pulsed eddy current testing can be used for detection of deformation structures at the same way. In next the correlation between the damage of the bulk material, the topographical deformation structure of the “smart sensor” and the parameter D_F will be presented.

Experiments

Sample

For the experiment flat bar tension specimen of the aluminium sheet AA2024 (AlCu4Mg1 with the yield stress σ_y = 260MPa, ultimate stress σ_u = 420MPa, fracture behaviour 8%) were used. The sample was provide by Airbus company. In the centre of the sample a “multi-scale smart skin” sensor, which was provided by Institute of Metal Physics in Kiev, was glued on the bulk-material, Figure 1. This sensor is a thick layer (~ 0.2-0.4 mm).

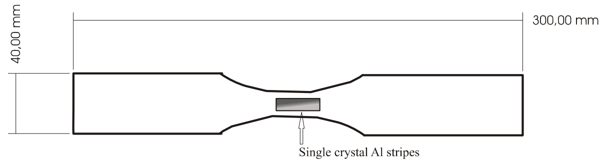

Figure 1. Al-alloy specimen thickness 3mm with glued single Al crystalline thin film 10x25 mm.

Fatigue test

The low cycle fatigue (LCF) tests were carried out in the elastic-plastic range. The fatigue test was done by tension-controlled guidance. The force time process was sinusoidal with the constant frequency υ = 20Hz. The maximal stress was equal to 300MPa and the minimal one was 20MPa (R = 0.07). The measurement of the optical images and eddy current signals (see below) was obtained at the minimal stresses.

Non destructive testing

Optical examination

The optical images of the "smart sensors" topography were taken in-situ by optical microscope (factor of magnifications - 10) in the stops between defined numbers of cycles. The initial image was transformed into a map with 256 gray tone scales. This step gone a more contrast to the surface images.

Eddy Current examination

The Pulsed Eddy Current (PEC) approaches were used. In our investigation we used pulsed eddy current signals generated by a waveform generator (repetition rate 0.7 MHz, pulse width 280 ns, and amplitude 2.5 V). The conventional eddy current (EC) sensor with $\varnothing$ = 9 mm were applied. A is a ferrite core sensor with two wound coils. The coil located directly at the core is the measurement coil and the exterior coil is the excitation coil.

Evaluating algorithm

For the evaluation of the fractal Dimension of the optical images the evaluating algorithm postulated by Müssigmann [8] was used. This algorithm is described in [7].

The Eddy Current relaxation time series are analyzed by using the difference auto correlation function, with is described in [7] also. The parameter q equal 2.

RESULTS

At first the topography of "smart sensor" during the cyclic tension tests was investigated by the optical method. The initial surface was smooth and flat. The regular band pattern was observed after approximately 2000 cycles. The bands were oriented along the loading direction. The rectangular grid-like pattern was observed after 10000 cycles. The distribution of the grid pattern through the "smart sensor" surface was not homogeneously. The areas with the grid pattern develop beside the areas of the band pattern. The behaviour of the two characteristic areas at the surface of the “smart sensors” was more pronounced with the increasing cycling. The difference in the development of both structures was caused by various adhesion forces of both plate areas, i.e. the altered constraint yield to rather different meso-structure development for the same fatigue damage of the bulk-material. The Figure 2 shows the metrology of the development of such different areas. The zone 1 contains band pattern, zone 2 - grid pattern and in between the transition zone 3 has a topography mixture of both zones 1 and 2.

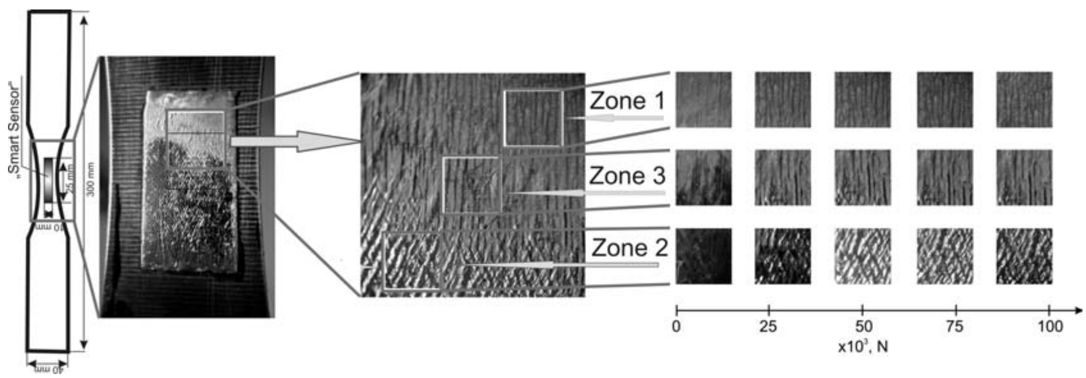

Figure 2. The Al alloy specimen with glued “Smart Sensor” examined during the fatigue test with the marked zones for fractal analysis. The zone 1 shows the band-pattern, zone 2 –grid-pattern and zone 3 - both the zone 1 and zone 2 pattern. Additionally, the developments of deformation structures at Al-stripe obtained by optical microscopy at zone1, zone 2 and zone 3 in dependence of the number of cycles N are presented.

Abovementioned effect of three zones was not detected at all examined samples. The samples with the stronger glued “smart sensors” to the bulk-material develop homogeneous pattern through whole stripe during fatigue damage. The Figure 3 shows the calculated D_F-parameter from the topography images in dependency of the damaged state of the bulk material. The $D_F(N/N_B)$-function increases till the sample fracture. Furthermore some indications were found that presented curve may have three stages observed for bulk-materials [7]. The first stage is characterized by irregular random microstructure, the band-like pattern are typical for next structural stage, and in the last stage multi-band or band crossing grid-like structure are developing.

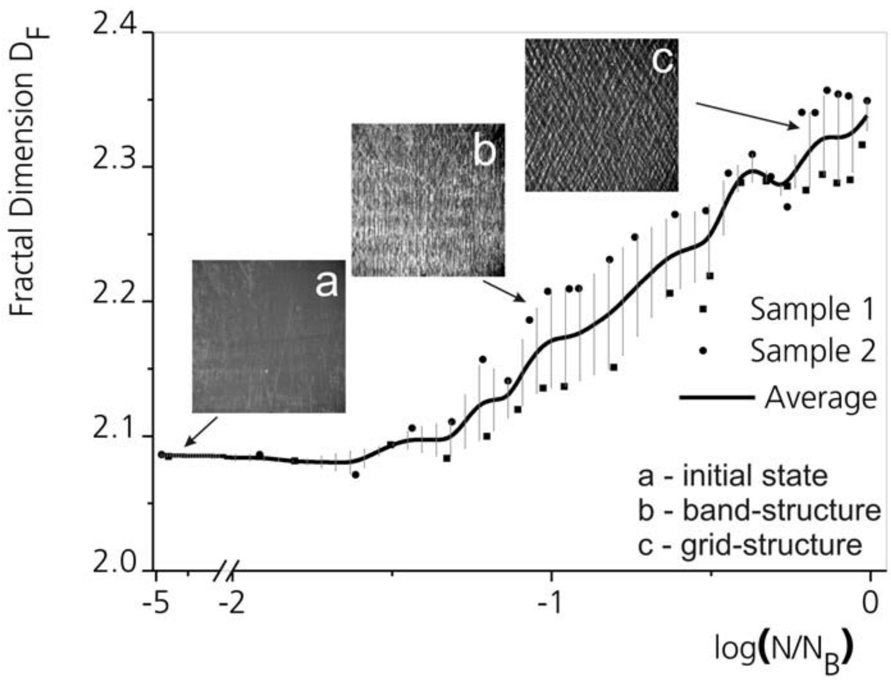

Figure 3. The fractal dimension D_F as a function of cycle number related to cycles number by the sample failure calculated from optical images by the use of Gaussian method during the on-line measurement of the samples 1 and 2. The examples of the three different deformation structures developed during these tests are included in the diagram.

The structure l changes of the “smart sensors” were also investigated by PEC technique. The EC and the optical measurements were done at the same position at the stripe. The Figure 3 shows the result of this procedure. The initial level of the fractal dimension was approximately 1.2. The fractal dimension grew up the appearance of band-like pattern at the Al-stripe surface with increasing fatigue damage. Then the behaviour of the fractal dimension stays almost constant. The final decrease of the D_F begins with the developed of the grid-like pattern on the Al stripe. On this account, the prediction of the bulk-material fatigue state by this way was impossible.

However, the first successful evaluation of the fatigue damage by the PEC at the common alloys of the aircraft industry technique will be presented in paper “Damage State Evaluation of Aircraft Alloys by Use of Pulsed Eddy Current Testing” by U. Cikalova,' et.al. in this proceedings.

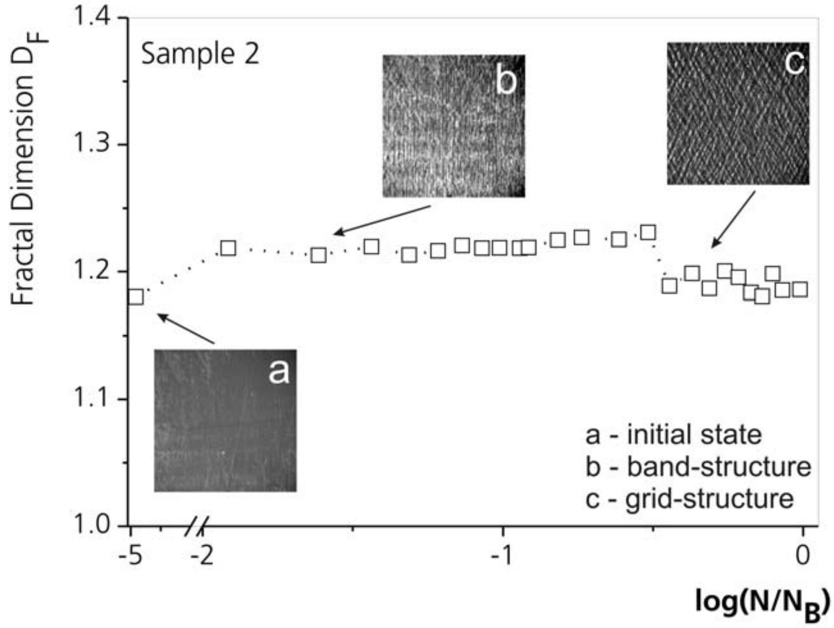

Figure 4. The fractal dimension DF as a function of cycle number related to cycles number by the sample failure calculated of optical images by the use of difference-autocorrelation function during the on-line measurement of the sample 2. The examples of the three different deformation structures developed during these tests are included in the diagram.

CONCLUSION

This paper described the application of the smart-designed thin film layers - "smart sensors" like a new non-destructive method for the monitoring of the fatigue state that can by used for the SHM concept. The result of the presented investigation shows that:

- The indication of three different damage stages - a) stochastic, b) band formation, c) multiband/grid state - of the "smart sensors" was confirmed.
- The fractal analysis of the optical images of the "smart sensors" topography during the fatigue tests can by used for the evaluation of the fatigue state of the whole samples.
- The $D_F(N/N_B)$-function can be affected by delamitation of the "smart sensor" and the crack appearance.

ACKNOWLEDGEMENTS

The authors thank for opportunity to take part at the INTAS project 04-80-7078 „Real-Time Multi-scale Composite System for Structural Health Monitoring of Fatigue Damage", especially to collaborate in a productive way with Dr. Ch. Paget, Prof. E. Zasimchuk, Dr. Y. Gordienko, Prof. V.E. Panin and Dr. P. Kusnetzov. For providing support in sample preparation authors thank the Airbus division in UK and the Institute of Metal Physics in Kiev, Ukraine. The authors express the gratitude to the teams of Siempelkamp Prüf- und Gutachter-Gesellschaft mbH Dresden for their support and supplying of experimental facilities.

REFERENCES

1. Ch. Paget, Bonded thin metallic foil sensor application for structural health monitoring of aeronautical structures, Phys. Mesomech., 11, No. 5–6 (2008) 308.
2. Yu.G. Gordienko, E.E. Zasimchuk and R.G. Gontareva, Unconventional deformation modes and surface roughness evolution in Al single crystals under restricted cyclic tension conditions, Mater. Sci. Lett., 22, No. 3 (2003) 241.
3. A. G. Protasov, Y. G. Cordienko, E. E. Zamischuk, Rev. of Pog. in Quantitative Non-destructive Evalution, , AIP Conference Proceeding, Vol 25 (2005) 820.
4. Y. G. Gordienko, R. G. Gontareva, Y. S. Schreiber, E. E. Zasimchuk, I. K. Zasimchuk, Two-Dimensional Rectangular and Three-Dimensional RhombicGrids Created by Self-Organization of Random Nanoextrusions, Ad. Engin. Materils, 8, No.10 (2006) 957.
5. E. E. Zasimchuk, Y. G. Gordienko, R. G. Gontareva, I. K. Zasimchuk, Equidimensional fractal maps for indirect estimation of deformation damage in nonuniform aircraft alloys , J. Mater. Eng. Perform., 12, No. 1 (2003) 68.
6. P. V. Kusnetzov, V. E. Panin, J. Schreiber, Fractal dimension as a characteristic of deformation stages of austenite stainless steel under tensile load, J. Theor. a. App. Fracture Mechanics 35, Issue 2 (2001)171.
7. J. Schreiber, U. Cikalova, and Ye. Vertyagina, Use of the fractal nature of spatial and temporal response behavior for materials damage characterization, in Proceedings of 6th Intern. Conf. on Low Cycle Fatigue, Berlin (2008) paper L100.
8. U. Müssigmann, Automation of visual surface inspection for quality control using fractal geometry, in Proceedings of Interkama Congress 92 supported by Eurofima, München/Wien (1992) 535.