

Experimental attempts for creep and fatigue damage analysis of materials – state of the art and new challenges

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Abstract

Development of creep and fatigue damage was investigated using destructive and non-destructive methods in materials commonly applied in power plants or automotive industry. In order to assess such kind of damage the tests for a range of different materials were interrupted for selected time periods (creep) and number of cycles (fatigue). As destructive methods the standard tension tests were carried out after prestraining. Subsequently, an evolution of the selected tension parameters was taken into account for damage identification. The ultrasonic and magnetic techniques were used as the non-destructive methods for damage evaluation. In the final step of the experimental programme microscopic observations were performed.

Keywords: creep, fatigue, damage, non-destructive methods

1. Introduction

Many testing techniques commonly used for damage assessments have been developed up to nowadays. Among them one can generally distinguish destructive and non-destructive methods. Having the parameters of destructive and non-destructive methods for damage development evaluation it seems to be reasonable their further analysis that should provide possible mutual correlations [1]. This is because of the fact that typical destructive investigations, like standard tests, give the macroscopic parameters characterizing the lifetime, strain rate, yield point, ultimate tensile stress, ductility, etc. without sufficient knowledge concerning microstructural damage development and material microstructure variation. On the other hand, non-destructive methods provide information about damage at a particular time of the entire working period of an element, however, without sufficient knowledge about the microstructure and how it varies with time. Therefore, it seems reasonable to plan damage development investigations in the form of interdisciplinary tests connecting results achieved using destructive and non-destructive methods with microscopic observations in order to find mutual correlations between their parameters. This is the main issue considered in this paper.

The microscopic observations of microstructural changes carrying out using traditional scanning electron microscopes are possible only after specimen failure, and additionally they suffer on high cost. The non-destructive methods are much more convenient and that is why they are more frequently used in engineering practice for periodic evaluation of the material degradation.

The resolution range of particular non-destructive tests covers the entire scope of structural effects and crystallographic defects [2], Fig. 1. Considering the detailed conditions and scopes of applying various methods significantly limits the possibilities to use them and makes it difficult to identify and analyse the fatigue damage evolution in the experimental way. This leads to a necessity of the constant improvement of existing non-destructive testing methods and of developing new measurement techniques that would be able to detect and carry out quantitative assessment of the structural failures resulting

from the development of processes leading to material fatigue and deterioration of its mechanical properties.

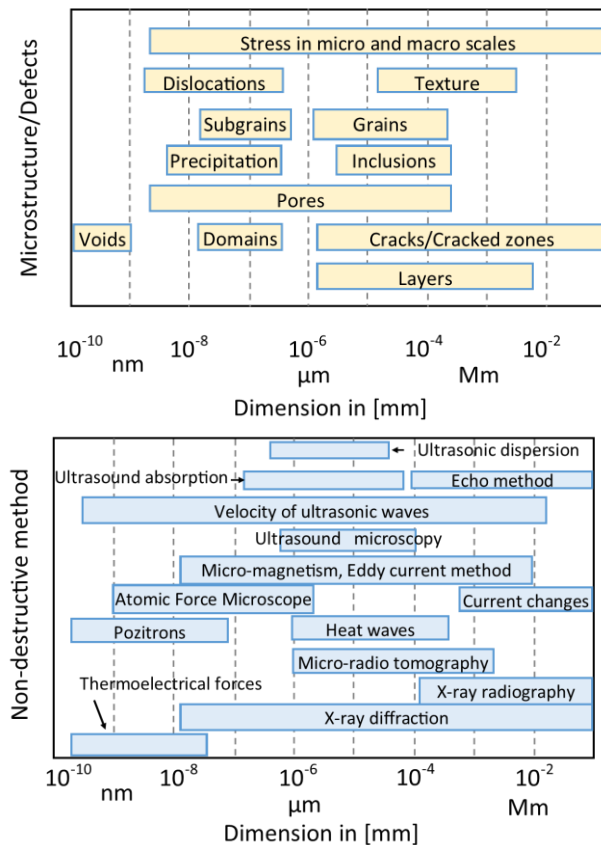


Figure 1: Dimensions of microstructural forms/defects and non-destructive methods suitable to monitor them [2].

The conventional non-destructive techniques (based on the measurement of ultrasonic wave velocities for example) are

sensitive to a material damage in the last stage of material life and do not give the answer into the question when a given element should be withdrawn from the exploitation? Therefore, there is the need to develop a new method based on a single or combination of non-destructive techniques allowing to estimate the microstructural and mechanical degradation observed at different stages of the exploited material.

2. Experimental attempts for creep damage analysis

2.1. Multiaxial creep tests

The results from uniaxial creep tests are not able to reflect complex material behaviour. Therefore, many efforts are focused on tests carrying out under multiaxial loading conditions. The well known method of creep rupture data from such tests analysis is through isochronous stress-strain curves obtainable from the standard creep curves [3]. It gives comprehensive graphical representation of material lifetime.

The curves of the same time to rupture determined on the basis of experimental programme are compared in Fig.2 with theoretical predictions of the three well known creep rupture hypotheses: (a) the maximum principal stress rupture criterion (Eqn 1), (b) the Huber-Mises effective stress rupture criterion (Eqn 2), (c) the Sdobyrev creep rupture criterion (Eqn 3). For the biaxial stress state conditions, realised in the experimental programme, the rupture criteria mentioned above are defined by the following relations:

$$\sigma_R = \sigma_{\max} = \frac{1}{2} \left(\sigma_{11} + \sqrt{\sigma_{11}^2 + 4\sigma_{12}^2} \right) \quad (1)$$

$$\sigma_R = \sigma_e = \sqrt{\sigma_{11}^2 + 3\sigma_{12}^2} \quad (2)$$

$$\sigma_R = \beta \sigma_{\max} + (1 - \beta) \sigma_e \quad (3)$$

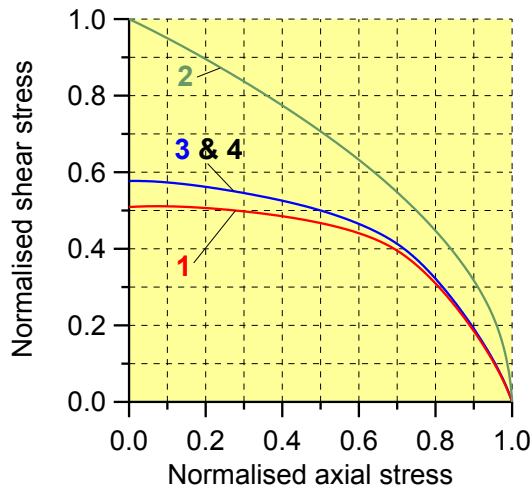


Figure 2: Comparison of the isochronous creep rupture surfaces ($t_R = 500$ [h]) determined for aluminium alloy (1 - experimental results; 2, 3, 4 - theoretical predictions using the maximum principal stress criterion; the effective stress criterion; and the Sdobyrev criterion, respectively)

As it is clearly seen, the best fit of the aluminium alloy data is obtained using the effective stress rupture criterion. It has to be

noting however, that the lifetimes predicted by this criterion are still quite far from experimental data.

2.2. New concepts of creep analysis

To assess damage using destructive method the specimens after different amounts of prestraining were stretched to failure [1, 4]. Afterwards, the selected tension parameters were determined (yield point, ultimate tensile stress) and their variations were used for identification of damage development. Ultrasonic and magnetic investigations were selected as the non-destructive methods for damage development evaluation. For the ultrasonic method, the acoustic birefringence coefficient was used to identify damage development in the tested steel. In the case of magnetic method a several damage sensitive parameters were identified, e.g. amplitude of U_b or U_a envelopes reflecting the Barkhausen effect (HBE) or magneto-acoustic emission (MAE) variation, respectively, their integrals, and coercivity.

Having selected parameters of destructive and non-destructive techniques, possible relationships between them were evaluated. The representative relationships are illustrated in Fig. 3a, b, c. As it is seen, except of the specimen prestrained up to 10.5% due to plastic flow, all results are ordered, and as a consequence, they can be well described by adequate functions depending on the type of prior deformation.

Diagram (a) in Fig. 3 shows relationship between integral of the U_b envelope amplitude - $\text{Int}(U_b)$ and ultimate tensile stress. The magnetic parameter is normalized to the value captured for the non-deformed specimen. Numbers in figure denote the level of prior deformation. Figure 3a allows concluding that integral $\text{Int}(U_b)$ of the Barkhausen noise may be used to estimate a level of the ultimate tensile stress of plastically deformed specimens. It has to be noticed however, that in the case of the material prestrained due to creep the situation is more complicated, since a non-unique relationship between R_m and $\text{Int}(U_b)_{\text{norm}}$ was found.

The relations in Fig. 3a indicate that the steel after plastic deformation, leading to higher values of R_m , can be characterised by lower values of magnetic parameters. This is because the prestrained material contains more dislocation tangles that impede domain walls movement. On the other hand the lower values of magnetic parameters can be attributed to the lower magnitudes of R_m for the steel after creep.

The results make evident that the MBE intensity varies significantly due to microstructure modification, however, in different ways depending on prior deformation type. For deformation higher than 2% this intensity decreases after plastic flow and increases after creep. Strongly non-linear character of plots in Fig.3a makes impossible direct estimation of mechanical parameters when only single magnetic parameter is used. Addressing the issue for practical application of the MBE measurement in assessment of mechanical properties of the damaged steel one can conclude that it is possible only then if at least two magnetic parameters will be taken into account. It can be seen in Fig. 3a that relative decrease of the $\text{Int}(U_b)$ with prestraining denotes plastic deformation while rapid increase of the $\text{Int}(U_b)$ associated with prestrain increase is observed for early stage of creep damage development.

Better correlation was achieved between R_m and coercivity H_c , Fig. 3b. As it is seen, except specimen prestrained up to 10.5% due to plastic flow, all results are ordered, and as a consequence, they can be well described by adequate functions depending on the type of prior deformation. The main disadvantage of the relationships between R_m and H_c , is related to the fact that it cannot distinguish a type of prior deformation for small prestrain magnitudes.

Similar remarks can be formulated for the relationships between R_m and acoustic birefringence coefficient B_{ak} , Fig. 3c.

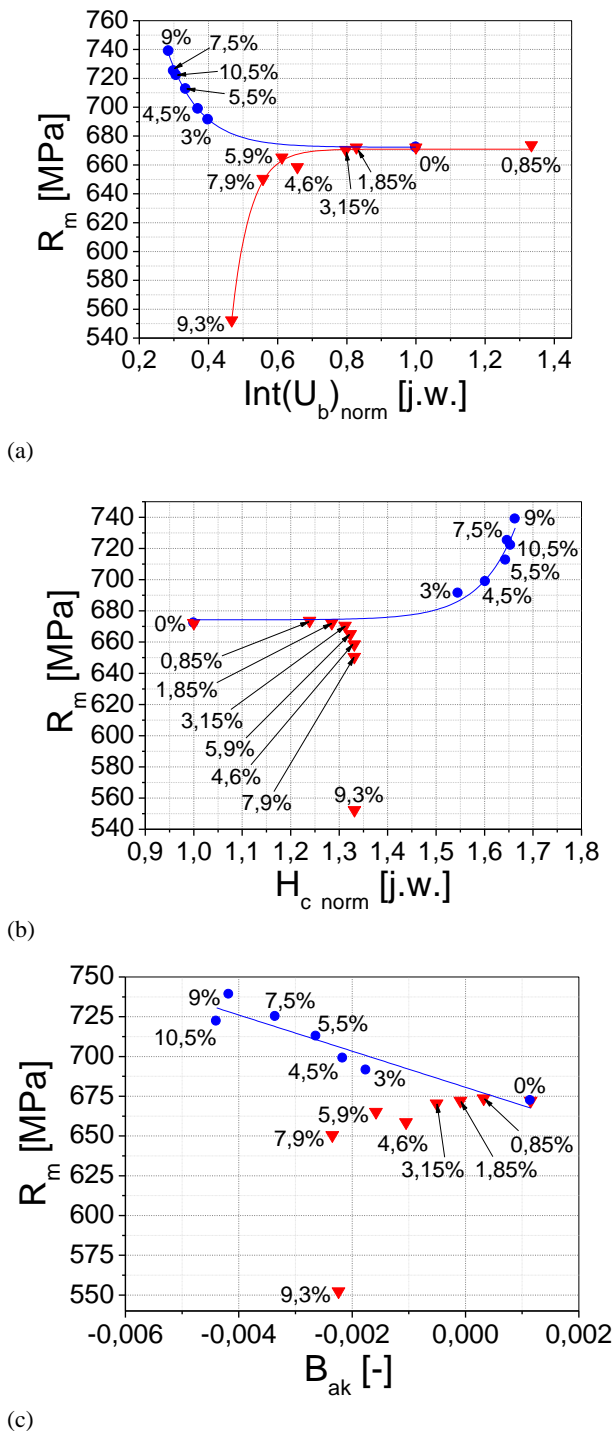


Figure 3: Variation of ultimate tensile stress of the X10CrMoVNb9-1 steel versus: (a) integral of the U_b envelope amplitude; (b) coercivity; (c) birefringence coefficient (triangles – steel after creep; circles – steel after plastic flow)

The relationships between selected destructive and non-destructive parameters sensitive for damage development show a new feature that may improve damage identification. In order

to provide more thorough analysis reflecting physical interpretation of the relationships obtained further investigations are necessary. Programmes of such tests should contain advanced microscopic observations using not only optical techniques, but also SEM and TEM.

3. Experimental attempts for fatigue damage analysis

The fatigue of structural materials is particularly important for the development of railway and air transport as well as power engineering. Fast introducing of new technologies in those sectors frequently leads to serious crashes. It is enough to mention two crashes of the first jet-propelled passenger aircraft called Comet, crash of the fast German railway in Eschede in 1998 or two jet crashes on the first transoceanic airway line in Poland in 1980 (Okęcie Airport in Warsaw) and in 1987 (Kabaty near Warsaw). All those tragic crashes were caused by the material fatigue, the nature of which has not been examined sufficiently.

Experimental determination of damage development requires on-line recording the material responses to the given cyclic loading during the whole experiment. Difficulty in conducting of this task is strengthened additionally by a lack of the effective fatigue damage measure describing properly effects of material degradation. Failure mechanics is relatively a new field of studies and the reference fatigue damage indicators described in scientific works should be treated only as suggested, but not verified and accepted problem solution. Monitoring of the changes in mechanical properties taking place under cyclic loads by means of recording stress and deformations of the measured sample section in consecutive cycles was an efficient technique enabling not only to define the number of cycles required to damage the specimen, but also to define the fatigue damage indicator and its evolution in the fatigue process.

Behaviour of materials within the range of high cycle fatigue (HCF), which means the stress amplitude is below the yield limit of a material, can be divided into two basic types in terms of mechanisms of damage development [5]. Behaviour of the first group of materials is described by the ratcheting generated by local deformation around voids, non-metallic precipitations and other defects of structure. Behaviour of the second group of materials undergoing cyclic loading is described by cyclic plasticity generated by slips on the level of grains and local slip bands. In both cases the changes of measured deformations are a sum of local deformations in the whole volume being measured. Cyclic loading in the range of HCF causes initiation of various mechanisms of damage development.

Initial defects in the form of inclusions initiate a localisation of damage, and as a consequence, its development in consecutive loading cycles. Their imaging (Figs. 4 and 5) helps not only to define the damage development mechanism, e.g. in the form of debonding or decohesion, but also provides the basis for modelling of their mechanisms development.

The metallographic methods are laborious and problematic due to the specific conditions of sample preparation. Usually they are mainly used after completion of the loading process or after its programmed suspension in the desired phase. Their significant limitations are due to the laborious procedures of sample preparation and the necessity to observe them after load removal. A few years ago, a unique research station has been constructed, with a servo-hydraulic testing machine equipped with digitally controlled signals of load, displacement, total or plastic strain, which can be used for monotonic stretching and compressing of specimens in the range of ± 100 kN and for low-

cycle fatigue tests (LCF) in temperature range up to 1100°C. The strength testing machine is connected to the set of scanning electron microscopes for examining the sample surface under monotonic load and microscopic observations with the resolution of μm . The second electron microscope enables an examination of the specimen surface under constant load, and microscopic observations with the nano-metric (nm) resolution. The specimen, after fixing and imposing the planned range of fatigue loads, is descended, together with the stress-testing machine frame, into a large vacuum chamber with the capacity of 2m^3 where the metallographic tests of the entire sample surface are carried out. The device is equipped also with EDX system (Energy Dispersive X-Ray) enabling to carry out local chemical analysis, and with EBSD system (Electron Back Scatter Diffraction) to image the metallographic orientation in the tested field. The first research station of such a type was installed in 2009 at the Institute for Material Science of the Erlangen-Nuernberg University in Germany.

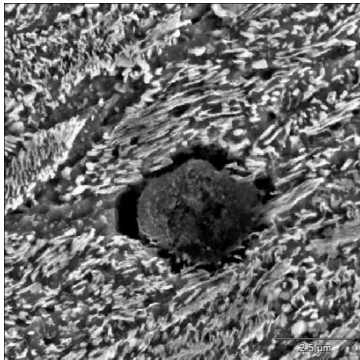


Figure 4: Microscopic image of failure due to fatigue carried out on X10CrMoVNb9-1 steel

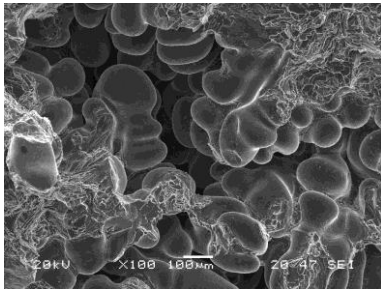


Figure 5: Microscopic image of failure due to fatigue carried out on A356-TiB₂

Among many fatigue testing programmes one can distinguish two basic directions: (a) investigations conducted by physicists and metallurgists focusing on trying to learn the mechanisms governing the process of fatigue; (b) theoretical and experimental investigations in order to create a phenomenological theory to allow quantitative description of the phenomenon. Both of these trends are currently developing in parallel.

3.1. Fatigue damage evaluation

In many cases the process of fatigue damage is controlled by more than one mechanism. The fatigue tests carried out on metallic materials and metal matrix composites have shown that the damage process occurred due to combination of cyclic plasticity and ratcheting mechanisms. Therefore, using adequate

damage indicators, Fig. 6, damage measure can be defined by the following relationship:

$$\varphi_N(\varepsilon_a^{in}, \varepsilon_m^{in}) = \sum_1^N |\varepsilon_a^{in}| + \sum_1^N |\varepsilon_m^{in}| \quad (4)$$

Hence, a definition of damage parameter takes the form:

$$D = \frac{\varphi_N - (\varphi_N)_{\min}}{(\varphi_N)_{\max} - (\varphi_N)_{\min}} \quad (5)$$

where φ_N – accumulated strain up to the current loading cycle, $(\varphi_N)_{\min}$ – accumulated strain at the first cycle, $(\varphi_N)_{\max}$ – accumulated total strain calculated for all cycles, in which damage measure is included in the form of equation (4).

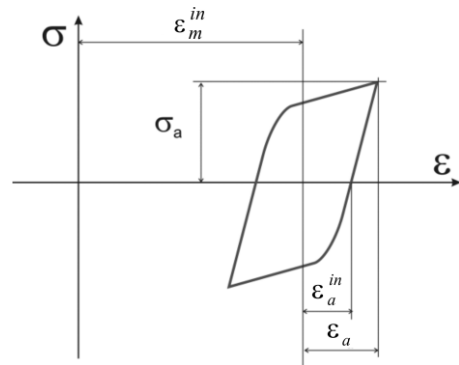


Figure 6: Illustration of strain damage indicators during fatigue conditions

The results published so far [e.g. 6, 7] confirm the correctness of the adopted methodology for damage analysis of the materials after service loads, that taking into account parameters responsible for cyclic plasticity and ratcheting.

3.2. Previous and new concepts of fatigue testing

In order to assess damage degree due to fatigue of the material in the as-received state and after exploitation the Wöhler diagrams may be elaborated that represent the number of cycles required for failure under selected stress amplitude. The results of such approach are illustrated in Fig. 7 for the 13HMF steel. As you can see, the Wöhler diagrams depending on the state of material differ themselves, thus identifying the fatigue strength reduction due to the applied loading history. Unfortunately, such method of degradation assessment of the material undergoing fatigue suffers on very high cost and additionally it is time consumable.

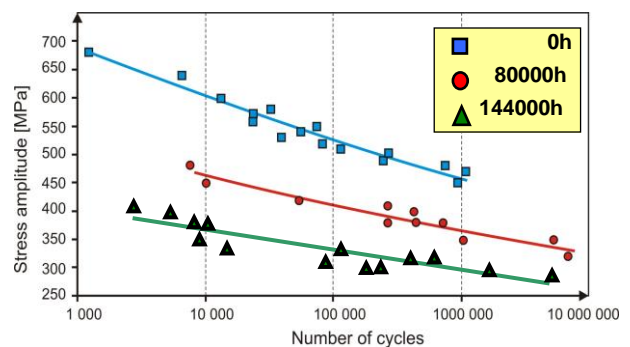


Figure 7: Wöhlers diagram for the 13HMF steel before (0h) and after exploitation (80 000h and 144 000h)

Therefore, searches are conducted for new solutions that would provide a better assessment of the fatigue damage development. In order to obtain this effect, an adequate damage parameter must be defined on the basis of the measurable indicators of its development. Selected proposals discussed in section (3.1) have been validated experimentally and the representative results will be presented here.

Force controlled high cycle fatigue tests (20 Hz frequency) were carried out on the servo-hydraulic testing machine MTS 858. During the tests, sine shape symmetric tension-compression cycles were applied to keep constant stress amplitude equal to 70 MPa and 350 MPa for metal matrix composite (Al/SiC) and X10CrMoVNb9-1 steel, respectively. Tests were performed at ambient temperature. Each cylindrical specimen manufactured from both materials was subjected to cyclic loading until fracture. A movement of the subsequent hysteresis loops along the strain axis was observed with an increasing number of cycle (Figs. 8 and 9). Simultaneously, a width of the subsequent hysteresis loops became almost unchanged for composite and became greater for the steel. Such behaviour identifies the ratcheting effect.

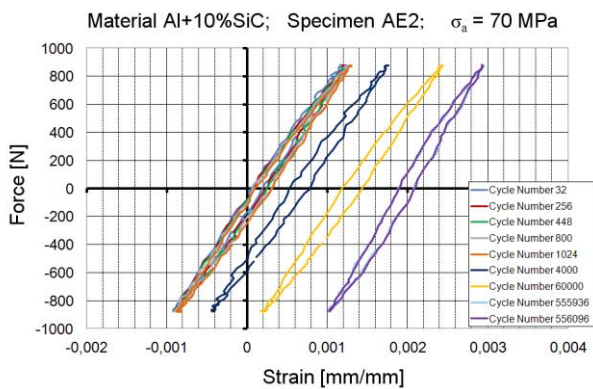


Figure 8: Hysteresis loops for selected cycles – the results for Al/SiC

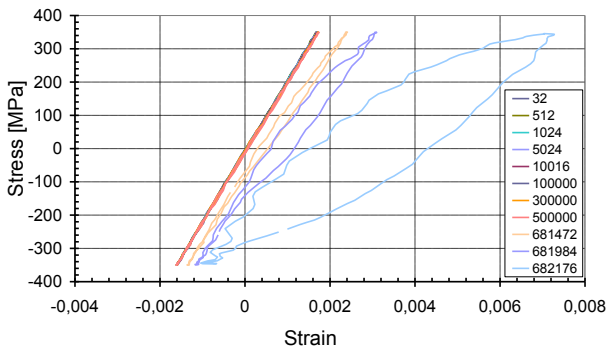


Figure 9: Hysteresis loops for selected cycles – the results for X10CrMoVNb9-1 steel

Since ratcheting is the dominant mechanism of the composite deformation, the mean strain was taken into account during a damage parameter calculation in the stable growth period. Hence, the damage parameter can be defined using equation (4) assuming that its first term is neglected. It is worth to noticed that the rate of damage is relatively high at the beginning of the period. Afterwards, it becomes slower (Fig. 10). In the case of X10CrMoVNb9-1 steel besides of ratchetting also cyclic plasticity mechanism is responsible (increase of hysteresis loop width) for damage development, Fig. 9. Taking into account

both mechanisms a variation of the damage parameter can be calculated using equations (4) and (5). In graphical form it is shown in Fig. 11.

Looking at the diagrams in Figs. 10 and 11 one can say that the linear damage accumulation rule cannot be applied for both tested materials. Moreover, it can be seen that the rate of damage parameter variation for composite depends on the SiC particle content. It increases with an increase of the SiC particle content at the initial stage of fatigue, Fig. 10.

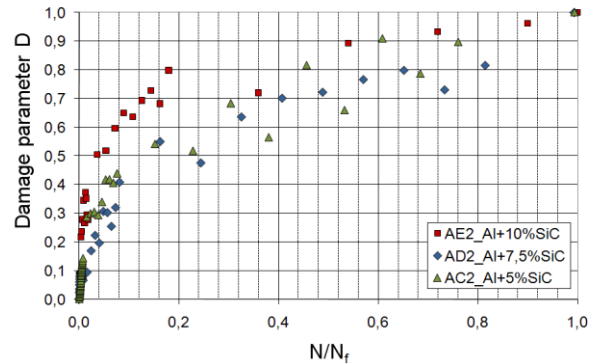


Figure 10: An influence of SiC content on damage parameter variation (stress amplitude 70MPa)

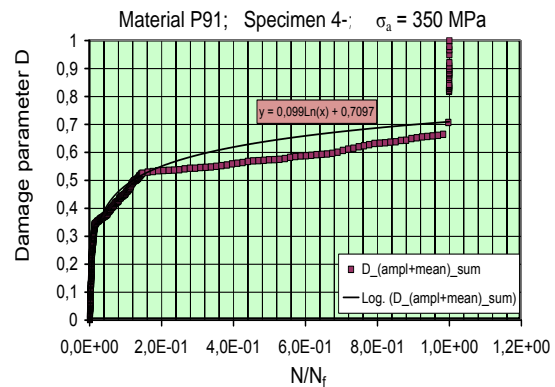


Figure 11: Damage parameter variation for X10CrMoVNb9-1 steel (stress amplitude 350MPa)

The examples of fatigue testing may be treated as an alternative method for damage evaluation of materials subjected to cyclic loads. Studies in which a variation of the hysteresis loop width and its movement were recorded for cycles under fixed constant stress amplitude have demonstrated that this procedure gives a possibility to assess safe operation period for materials in question and there is no need to perform so many experiments, as it is required for the Wöhler diagram determination. The proposed method of assessing fatigue damage evolution makes it possible to: determine damage indicators; define damage parameter; assess fatigue and stress levels to find ranges in which an accumulation of damage can be described by the linear law.

Another very promising attempts in the fatigue damage analysis are related to relatively new techniques such as Electronic Spackle Pattern Interferometry (ESPI) or Digital Image Correlation (DIC). Some preliminary results of the ESPI usage will be presented here. The cast aluminum alloy AlSi7MgCu0.5 for automotive engine heads [6] was tested after exploitation cycles.

Opportunity for strain/stress components measurement of a specimen using ESPI is presented in Fig. 12. The specimen was cut from automotive engine head (cast aluminum alloy AISi7MgCu0.5). Such heads were cast according to the standard procedure that ensures degassing. The ratio of the average porosity was 6%. Observing the strain and stress distributions in Figs. 12 and 13 a serious problem can be noticed, i.e. an averaging of the accuracy of the strain components in the entire volume of the geometrically homogeneous specimen. In this group of materials the development of fatigue damage takes place around various drawbacks, mainly in the form of voids formed in manufacturing processes such as casting. Besides of density and distribution of defects in the volume of tested specimen, the specimen size, and location of individual defects are important factors of the fatigue damage initiation and further development. Development of local strain components around defects leads to ratcheting, i.e. the incremental rise of the strain components being in agreement with acting stress direction. This group includes not only all cast alloys, but also the whole range of modern metal matrix composites.

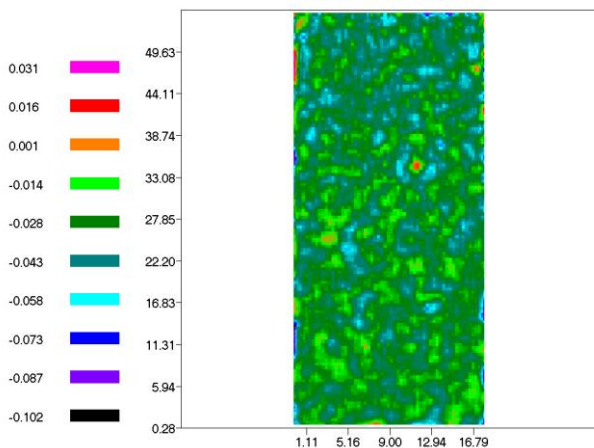


Figure 12: Strain component distribution map for z direction on the plane specimen surface (cross section 18×4 mm) under load of 1.2 kN

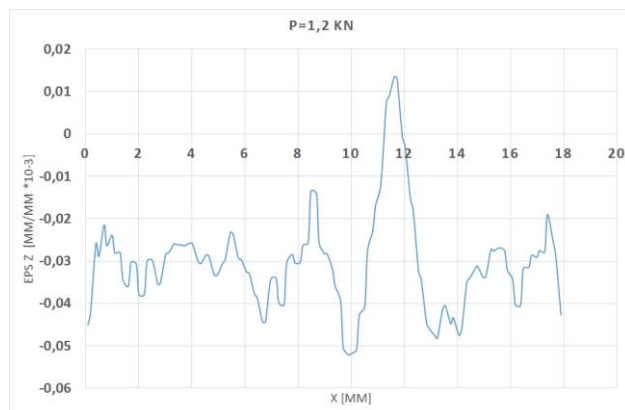


Figure 13: Transversal distribution of the stress component along z axis

Solving problems related to development of fatigue damage, degradation of the mechanical properties of structural materials, as well as modeling of the mechanical properties necessary to

simulate the behaviour of the structure under loading is based mainly on experimental data from tests under uniaxial stress states. However, for such purposes also data coming from complex stress state experiments are required. The testing technique under complex stress states gives full information about the mechanical properties of structural materials, necessary for parameters determination during numerical modeling. In this context either ESPI or DIC are very helpful since monitoring of the phenomena related to the fatigue, as the process initiating locally, requires the full-field observations of the displacement brought by cyclic loading. Both these methods enable determination of the displacement distribution on the specimen surface, and thus, also strain and stress concentration spots resulting from the defect.

4. Conclusions

The results clearly indicate that selected ultrasonic and magnetic parameters can be good indicators of material degradation and can help to locate the regions where material properties are changed due to prestraining.

Creep or fatigue analysis should be based on the interdisciplinary tests giving a chance to find mutual correlations between parameters assessed by classical macroscopic destructive investigations and parameters coming from the non-destructive experiments. Such relationships should be supported by thorough microscopic tests, giving as a consequence, more complete understanding of the phenomena observed during damage development.

Application of the full-field observation methods (ESPI, DIC) enables localization of the initial spot of the failure resulting from the cyclic stress and monitoring of its development as well.

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