Proceedings of the 4th International Conference on Nonlinear Dynamic
ND-KhPI2013
June 19-22, 2013, Sevastopol, Ukraine

Damage Indicators During Fatigue of Metal Matrix Composites

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Abstract
Selected damage measures applied for degradation description of engineering materials subjected to fatigue loading conditions are presented. In addition to well-known measures the new concepts of fatigue damage development are discussed using known mechanisms of cyclic plasticity and ratcheting. Their usefulness was studied on the basis of experimental results for modern metal matrix composites commonly applied in many branches of the industry.

Keywords
Damage, fatigue, composites

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Introduction

First investigations aimed to clarify the phenomenon of fatigue were already carried out in the first half of the nineteenth century. The tests in this area conducted Albert in 1838. The first experimental programme important from the scientific point of view was executed for selected metals by A. Wöhler in 1860. From that moment, intensifying progress of material testing under fatigue conditions can be observed and it is continued to this day. Especially in recent years there has been an increased interest in the problems of fatigue and at the same time enormous progress in this field. This is mainly because of an increase either in the level of loading or degree of loading complexity in the number of operating units. As typical examples one can indicated aviation where aircraft speed and weight increase or energetics with rapid temperature increase of devices producing energy. The observed technical progress enforces a development of fatigue testing methods, because the safety of people depends many times on the results of these tests. Modern passenger aircrafts may be operated, if parallel simulation fatigue tests are carrying out, the results of which allow for the safe exploitation of machines being currently in use. Among fatigue tests one can distinguish two basic directions:

- investigations conducted by physicists and metallurgists focusing on trying to learn the mechanisms governing the process of fatigue,
- 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 parallelly [e.g. 1-6].

1. Experimental evaluation of fatigue damage

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.1 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.

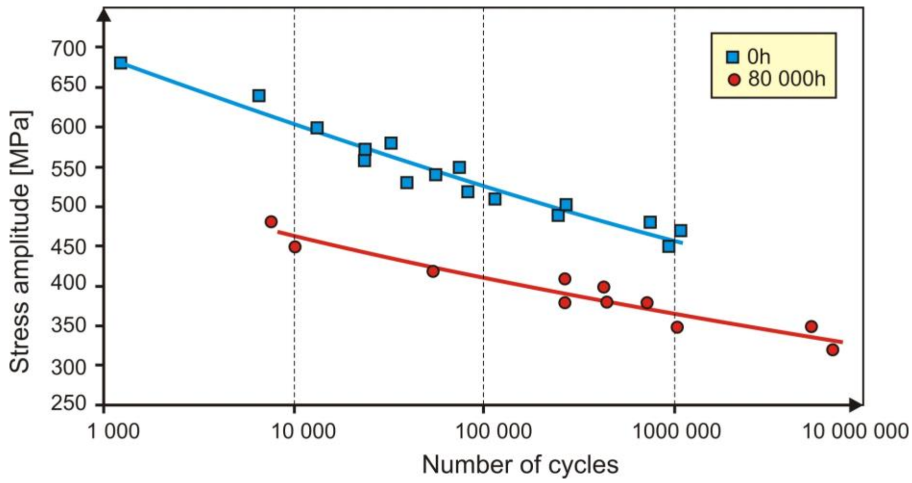

Figure1. Wöhlers diagram for the 13HMF steel before (0h) and after exploitation (80 000h) [7]

Therefore, searches are conducted continuously for new solutions that would provide a better assessment of the fatigue damage development. To obtain this effect, an adequate damage parameter must be defined on the basis of the measurable indicators of its development. Selected proposals are discussed in the next section of this paper.

2. Indicators and measures of fatigue damage

The essence of fatigue are changes in the structure of a material due to operational stresses, movement of lattice defects (slip dislocations, vacancies migration), the concentration of these defects in areas where they face further obstacles to movement (grain boundaries, inclusions), forming the so-called persistent slip bands, and other processes, such as stress/temperature-induced phase transformations, and diffusion processes. The net effect of these phenomena is the nucleation and growth of microcracks, and in the final stage of damage development formation of the dominant crack in the material. Such crack develops subsequently in the element of structure until it reaches a critical size. After that the service loading applied can cause its uncontrolled growth leading to structural failure.

The fatigue damage development is associated with nucleation and growth of micro-cracks. In the theoretical papers concerning fatigue damage a size of the micro-cracks located in the material was assumed as the fatigue damage measure. The most common idea of damage measure is the surface density of micro-cracks in the representative unit volume of a material (Kachanov, 1958 [8]). In this case the damage parameter is no scalar, since it depends on the direction. Such a concept has been developed further by other researchers, and as a consequence, in 1981 Murakami [9] introduced the second order tensor as a measure of damage. This form of damage parameter is still often used by a number of researchers. The disadvantage of such defined parameter, however, is that it cannot be measured in a period prior to the formation of a dominant crack in the material by any of the currently known methods. Nevertheless, experimental study of a damage measure changes in material during construction operation or laboratory tests is a necessary condition for fatigue life prediction and assessment of the risks associated with further safe operation of the structure. Therefore, intensive searches are still ongoing in order to find measurable parameter representing fatigue damage of structural materials.

The behaviour of materials under high cycle fatigue (HCF) for stress amplitude of levels below the yield point can be divided into two basic types according to their mechanisms of damage development.

The behaviour of the first group may be described by cyclic plasticity generated by dislocation movement at the level of local grains and slip bands. In this case a non-elastic strain is the damage indicator characterized by the width of the hysteresis loop at total unloading of the material, equation (1), Figs. 2a, 3.

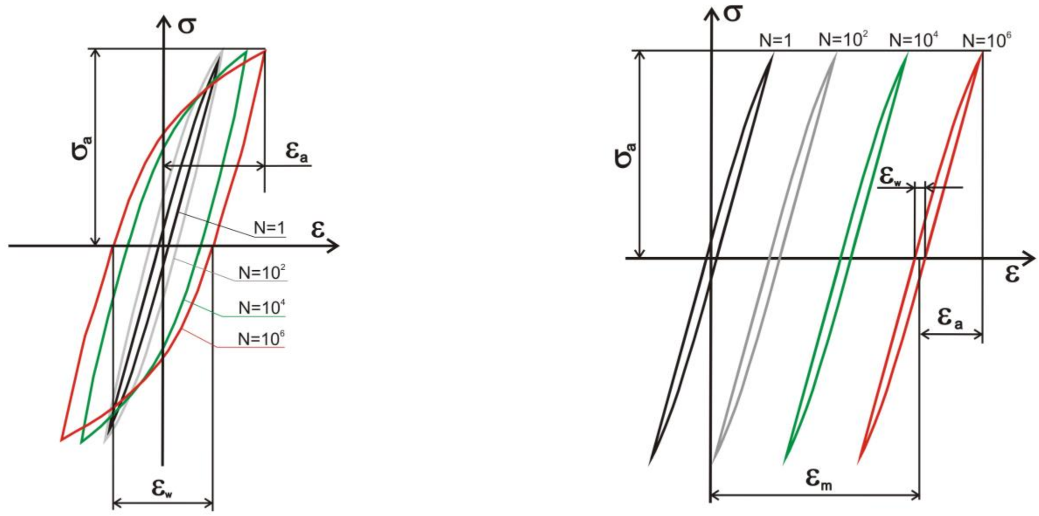

Figure 2. Hysteresis loops depending on the damage mechanism: (a) cyclic plasticity, (b) ratcheting

$$\varepsilon_a^{in} = \frac{\varepsilon_{\max}(F=0) - \varepsilon_{\min}(F=0)}{2} \tag{1}$$

Fatigue damage measure can be defined in such a case by the following relationship:

$$\varphi_N(\varepsilon_a^{in}) = \sum_1^N \left|\varepsilon_a^{in}\right| \tag{2}$$

Using equation (2) a damage parameter taking values varying within <0;1> can be written in the following way:

$$\mathrm{D} = \frac{\varphi_N - (\varphi_N)_{\min}}{(\varphi_N)_{\max} - (\varphi_N)_{\min}} \tag{3}$$

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.

The behaviour of the second group of materials subjected to cyclic loading is described by ratcheting generated by local deformation around the voids, inclusions and other defects of the microstructure. In this case the damage indicator is atributted to the mean inelastic strain describing a shift of the hysteresis loop under unloaded state. It can be defined by the following expression,

$$\varepsilon_m^{in} = \frac{\varepsilon_{\max}(F=0) + \varepsilon_{\min}(F=0)}{2} \tag{4}$$

Its graphical interpretation is shown in Fig.2b.

Applying damage indicator in the form of equation (4) the damage measure can be defined as:

$$\varphi_N(\varepsilon_m^{in}) = \sum_1^N \left|\varepsilon_m^{in}\right| \tag{5}$$

and thus damage parameter taking values varying within <0;1> can be expressed by the relationship of the structure of equation (3). The sign of absolute value at relationships (2) and (5) results from the fact, that the hysteresis loops of the subsequent cycles may move either in the positive or negative direction of the strain axis, Fig. 4.

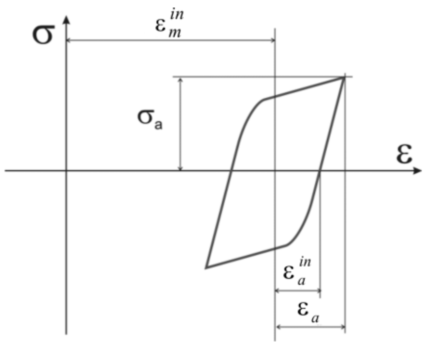

Figure 3. Ilustration of strain damage indicators during fatigue conditions

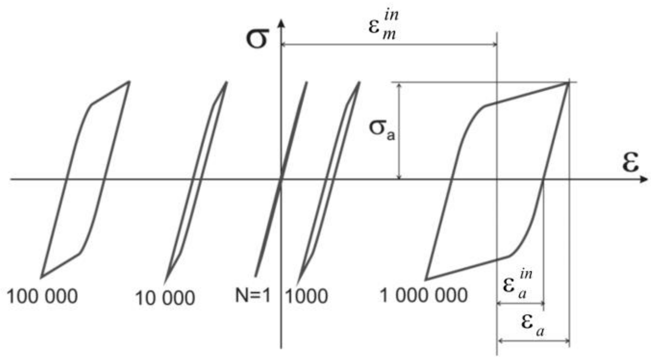

Figure 4. Variants the hysteresis loops movement

In both cases, changes of strain taken for the entire measuring volume of the specimen is the sum of local deformation developing around defects in the form of nonmetallic inclusions and voids for the first group of materials or developing slides at the consecutive grains in the case of the second one. Evolution of the hysteresis loop depending on the damage mechanism for the loads corresponding to stress levels below the yield point is shown in Fig. 2.

In many cases the process of fatigue damage is controlled by more than one mechanism. The fatigue tests carried out on metal matrix composites have shown that the damage process occurred due to combination of cyclic plasticity and ratcheting mechanisms. Therefore, using damage indicators determined on the basis of formulas (1) and (4), damage measure can be defined by the following relationship:

$$\varphi_N(\varepsilon_a^{in}, \varepsilon_m^{in}) = \sum_1^N \left|\varepsilon_a^{in}\right| + \sum_1^N \left|\varepsilon_m^{in}\right| \tag{6}$$

Hence, a definition of damage parameter takes the form of equation (3), in which damage measure is included in the form of equation (6). The results published so far [e.g. 1, 10, 11] 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. Application of damage parameters for fatigue tests analysis of MMC

Damage analysis presented in section 2 and confirmed for the conventional materials [1] was applied in this research for the metal matrix composite. The Al/SiC composite was prepared from a commercial Al powder with a purity of 99.7% and an average particle size of 6.74 μm (delivered by the Bend-Lutz Co) and the reinforcing phase was made of the SiC powder of 99.8% purity and an average particle size of 0.42 μm (Alfa Aesar Co). The technological process included several stages. In the first stage of process the powders were mixed so as to obtain (Al+x vol.% + SiC) mixtures, where x ranged from 0% to 10% and was changed at an increment of 2.5. The mixtures were homogenized, for 6h, in a polyethylene vessel using a suspension of isopropyl alcohol and Al_2O_3 balls, then dried and granulized at room temperature on a sieve with the mesh size of #0.25 mm. In the next stage, the powder mixtures were subjected to isostatic consolidation at the pressure p = 245 MPa. The samples thus obtained were machined to give them the desired shape (cylindrical) and dimensions (radius r=40 ± 1 mm, length ~50 mm). The final stage of the technological process included direct extrusion of the prepared samples in the KOBO 100T horizontal hydraulic press, equipped with a reversely rotating die whose movement was transmitted onto the extruded material so that its deformation path varied.

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 65 and 70 MPa. Tests were performed at ambient temperature. Each cylindrical specimen manufactured from the Al/SiC rod 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 (Fig. 5). Simultaneously, a width of the subsequent hysteresis loops became almost unchanged. Such behaviour identifies the ratcheting effect. Only insignificant increase of inelastic strain amplitude was observed (Fig. 6).

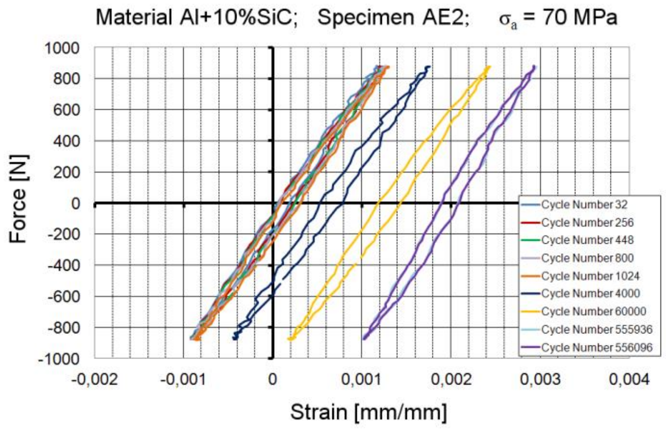

Figure 5. Hysteresis loops for selected cycles

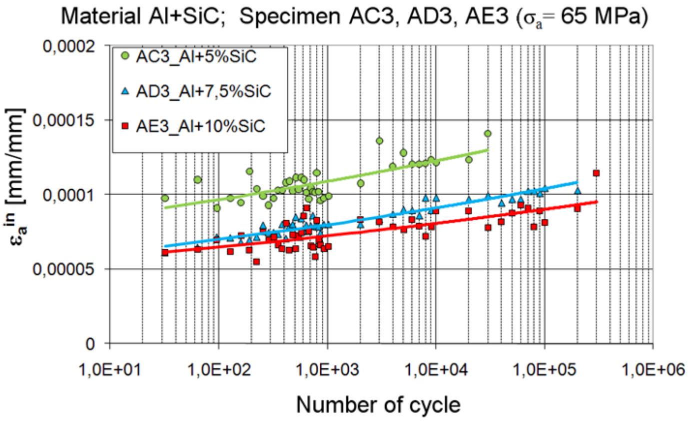

Figure 6. Inelastic strain amplitude ε_a^{in} for selected cycles

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 (3). It is worth to noticed that the rate of damage is relatively high at the beginning of the period. Afterwards, it becomes slower (Fig. 7).

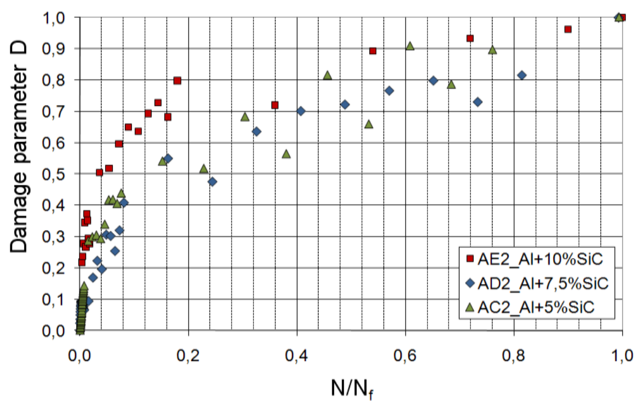

Figure 7. An influence of SiC content on damage parameter variation (stress amplitude 70MPa)

Such a phenomenon indicates that the linear damage accumulation rule cannot be applied for the Al/SiC MMC. Moreover, it can be seen that the rate of damage parameter at the initial stage of fatigue increases with an increase of the SiC particle content.

Conclusions

The paper presents an alternative method for damage evaluation of materials subjected to fatigue 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 composites 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, to define damage parameter and to assess fatigue and stress levels to find ranges in which an accumulation of damage can be described by the linear law.

An increase of the SiC content improved the fatigue resistance, and moreover, it increased the rate of hardening during monotonic tensile tests. Hence, it can be concluded generally that the SiC reinforcement led to the material properties improvement. However, it has to be mentioned that a larger content of the SiC particles may lead to generation of their clusters, which often include incoherent particles. Since is well known that the main part of the specimen loading is carrying out by reinforcements, such type of clusters do not contribute to tensile load transfer, and therefore, they can be treated as voids in the structure of a material.

Acknowledgements

The results have been obtained within the project KomCerMet (project No POIG.01.03.01-00-013/08 with the Polish Ministry of Science and Higher Education) in the framework of the Operational Programme Innovative Economy 2007-2013. The material was produced by team of prof. A. Olszyna (Warsaw University of Technology).

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