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FATIGUE DAMAGE OF Al/SiC COMPOSITES – MACROSCOPIC AND MICROSCOPIC ANALYSIS

MAKROSKOPOWA I MIKROSKOPOWA ANALIZA USZKODZENIA ZMĘCZENIOWEGO KOMPOZYTÓW Al/SiC

The results of comparative examinations of mechanical behaviour during fatigue loads and microstructure assessment before and after fatigue tests were presented. Composites of aluminium matrix and SiC reinforcement manufactured using the KoBo method were investigated. The combinations of two kinds of fatigue damage mechanisms were observed. The first one governed by cyclic plasticity and related to inelastic strain amplitude changes and the second one expressed in a form of ratcheting based on changes in mean inelastic strain. The higher SiC content the less influence of the fatigue damage mechanisms on material behaviour was observed. Attempts have been made to evaluate an appropriate fatigue damage parameter. However, it still needs further improvements.

Keywords: fatigue, damage, metal matrix composites, microstructure

W artykule zaprezentowano wyniki mechanicznych badań w warunkach zmęczenia oraz badań mikrostrukturalnych przed i po testach zmęczeniowych. Badaniom poddano kompozyty o osnowie aluminiowej wzmocnionej węglikiem krzemu SiC wyprodukowane przy użyciu metody KoBo. Zaobserwowano kombinację dwóch mechanizmów uszkodzenia zmęczeniowego. Pierwszy związany z cykliczną plastycznością, a co za tym idzie ze zmianami amplitudy odkształcenia niesprężystego oraz drugi wyrażający się w formie ratchetingu oparty na zmianach średniego odkształcenia niesprężystego. Zaobserwowano również słabnący wpływ mechanizmów uszkodzenia zmęczeniowego na zachowanie badanego kompozytu wraz ze wzrostem zawartości SiC. Podjęto próbę oszacowania odpowiedniego parametru uszkodzenia zmęczeniowego, jednakże wymaga on dalszych udoskonaleń.

1. Introduction

The fatigue process can be assessed in many ways. The most often performed fatigue tests enable to elaborate the Wöhler diagrams. Using the method one can receive information on fatigue life at different stress amplitudes and fatigue endurance. Another approach to fatigue process assessment is based on tensile tests carried out on specimens after given number of fatigue cycles. It gives knowledge about mechanical properties of materials after fixed fatigue history. It has to be noticed however, that these approaches for fatigue analysis do not give sufficient knowledge related to damage taking place during fatigue process.

Many attempts have been made to evaluate an appropriate fatigue damage parameter [1-8]. Kaczanow proposed as a damage indicator the density of microcracks identified at the surface in a given volume. Murakami developed the method and proposed damage parameter to be defined as a second order tensor. Many other approaches have also been used to evaluate fatigue damage indicator. They were based either on the nondestructive tests: ultrasonic, acoustic, magnetic, eddy-currents, or destructive ones where damage indicator was taken as: density, stress, strain or elastic modulus.

Recently, a promising idea of fatigue damage indicator was proposed by Socha [1, 2] on the basis of damage accumulation expression given by Azari et al. [4, 5]. In this case damage parameter is defined using the inelastic strain amplitude. The parameter was successfully applied for steels where the main fatigue damage mechanism is based on cyclic plasticity. Dietrich proposed the mean inelastic strain as a fatigue damage indicator for materials which exhibit ratcheting instead of cyclic plasticity [6-8]. There are materials, e.g. composites, for which cyclic plasticity and ratcheting can be observed simultaneously during tests. For such materials Dietrich proposed fatigue damage parameter based on a sum of the mean inelastic strain and inelastic strain amplitude. Further investigations on inelastic strain changes during subsequent cycles led to evaluation of the fatigue damage parameter calculation on the basis of modified fatigue damage indicator. The indicator proposed by Dietrich was based on a sum of absolute values of changes of inelastic strain amplitude and mean inelastic strain for cycles taken into account. However, the fatigue damage parameter calculated using the modified fatigue damage indicator was sensitive to the number of data that had been collected during tests.

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2. Tests details

Aluminium based metal matrix composites (MMCs) reinforced by SiC particles were investigated. The materials were produced in the form of long rods with diameter equal to 8 mm using the KoBo method [8-11]. Two series of composites with slightly different technological parameters were taken into account. Fatigue cylindrical specimens manufactured from the rods were used in all experiments. Experimental programme contained tension-compression fatigue tests with R = -1. The tests were force controlled with stress amplitude equal to 65 and 70 MPa for the first series of composites, while for the second one it was 70 and 100 MPa. Fatigue tests were carried out on the MTS 858 servo-hydraulic testing machine at the frequency equal to 20 Hz. Force, displacement and strain signals were collected. An extensometer was mounted on each specimen in order to measure strains that were used subsequently to calculate automatically an inelastic strain amplitude and mean inelastic strain for each cycle. Tests were performed at ambient temperature.

Microstructural observations were carried out using a light microscope and scanning electron microscope (SEM) for materials in the as received state and after fatigue tests. Fracture surfaces after fatigue tests were also analysed.

3. Results of fatigue tests

Fatigue damage parameter was calculated on the basis of fatigue test results for the first series of composites. Since ratcheting was a dominant damage mechanism during the fatigue tests, mean inelastic strain was taken into account as a fatigue damage indicator in the stable growth of damage period. The results were presented in a separate paper [8]. It is worth emphasizing that the rate of damage was relatively high at the beginning of stable damage growth period and subsequently it became lower. Moreover, it was observed that the increase rate of fatigue damage parameter during initial stage of fatigue rose with an increase of SiC particle content. Values of mean inelastic strain were lower for higher reinforcement content, which indicates fatigue strain resistance improvement with an increase of SiC content.

For the second series of composites it was possible to apply higher stress amplitude equal to 100 MPa. Unfortunately, mean inelastic strain not only increased but also decreased during subsequent cycles (Fig. 1), which made it impossible to use simple mean inelastic strain as a fatigue damage indicator.

Looking at the mean inelastic strain (Fig. 1) and inelastic strain amplitude (Fig. 2) variations during subsequent cycles, one can conclude that in majority cases the highest values were obtained for the matrix material in comparison to the composites. That means higher fatigue strain resistance for aluminium reinforced by SiC in comparison to the aluminium itself. It is worth to notice that for the Al+2,5%SiC similar values of the mean inelastic strain were obtained as those for the Al+10%SiC achieved. However, the former composite exhibited higher lifetime what means its better fatigue properties.
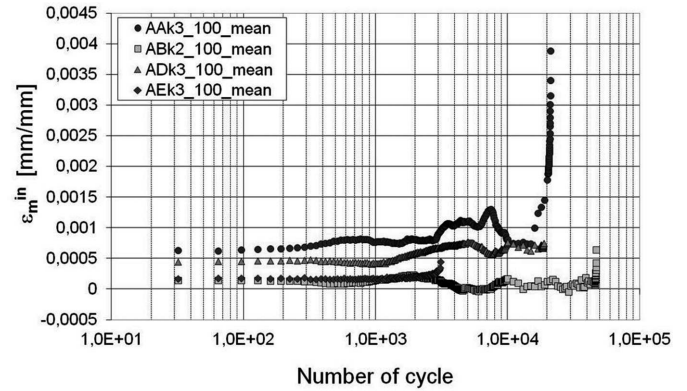

Fig. 1. Mean inelastic strain for Al/SiC composite (second series) tested at stress amplitude equal to 100 MPa. AAk3 – Al matrix, ABk2 – Al+2,5%SiC, ADk3 – Al+7,5%SiC, AEk3 – Al+10%SiC
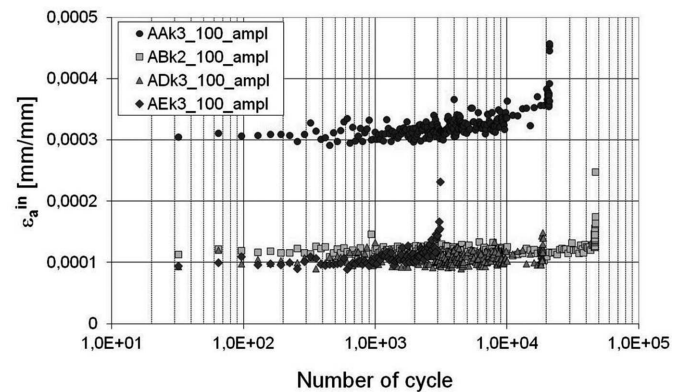

Fig. 2. Inelastic strain amplitude for Al/SiC composite (second series) tested at stress amplitude equal to 100 MPa. AAk3 – Al matrix, ABk2 – Al+2,5%SiC, ADk3 – Al+7,5%SiC, AEk3 – Al+10%SiC

Depending on the level of stress amplitude and SiC content, different changes of hysteresis loops were observed during fatigue tests. Ratcheting was the dominant damage mechanism for the matrix tested at stress amplitude equal to 70 MPa (Figs. 3 and 4). In the case of matrix tested at 100 MPa stress amplitude cyclic plasticity combined with ratcheting were the main fatigue damage mechanisms (Figs. 5 and 6). The composite with 7,5% of SiC tested at 70 MPa exhibited ratcheting towards negative strain values (Fig. 7), while hysteresis loops during fatigue tests of the Al+10%SiC under the same stress amplitude nearly did not change during subsequent cycles (Fig. 8). The Al+2,5%SiC tested at the stress amplitude equal to 100 MPa exhibited cyclic plasticity combined with ratcheting (Figs. 9 and 10). In cases of higher SiC content an influence of damage mechanisms on hysteresis loops was smaller.

Since the damage mechanisms for the tested composites were not the same, and the inelastic strain levels not only increased but also decreased during subsequent cycles, some attempts have been made to use modified fatigue damage indicator to calculate fatigue damage parameter. Since the proposed indicator is sensitive to the number of cycles taken into account, the method is still developing.
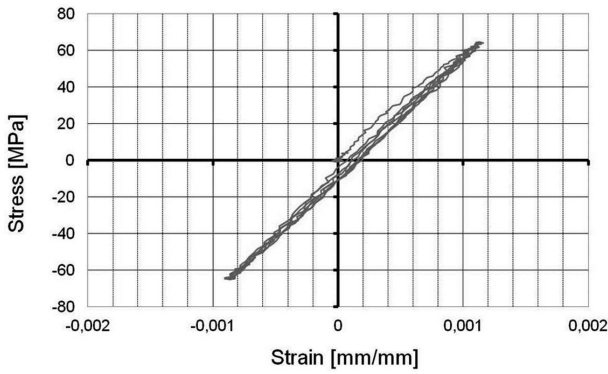
Fig. 3. Hysteresis loops for the initial cycles of fatigue tests. Material Al (second series) tested at stress amplitude equal to 70 MPa
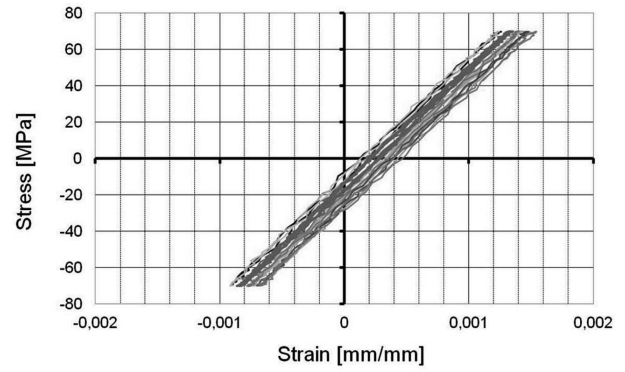

Fig. 4. Hysteresis loops for the cycles over 100 of fatigue tests. Material Al (second series) tested at stress amplitude equal to 70 MPa
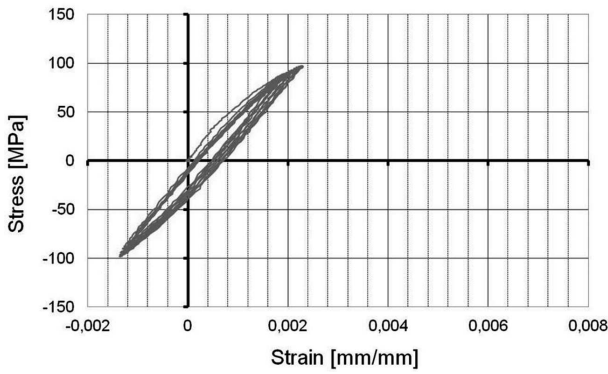

Fig. 5. Hysteresis loops for the initial cycles of fatigue tests. Material Al (second series) tested at stress amplitude equal to 100 MPa
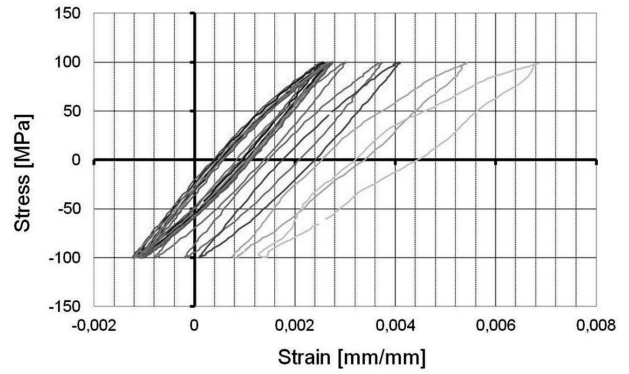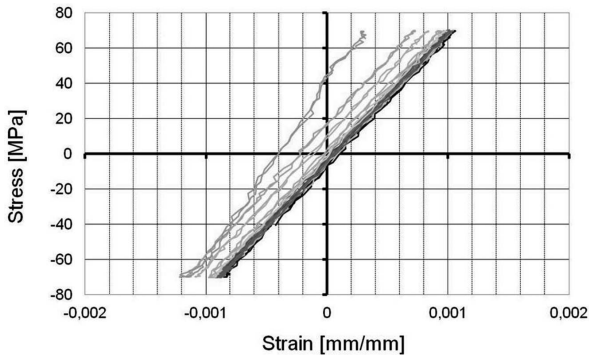

Fig. 6. Hysteresis loops for the cycles over 100 of fatigue tests. Material Al (second series) tested at stress amplitude equal to 100 MPa

Fig. 7. Hysteresis loops for the cycles over 100 of fatigue tests. Material Al+7,5%SiC (second series) tested at stress amplitude equal to 70 MPa
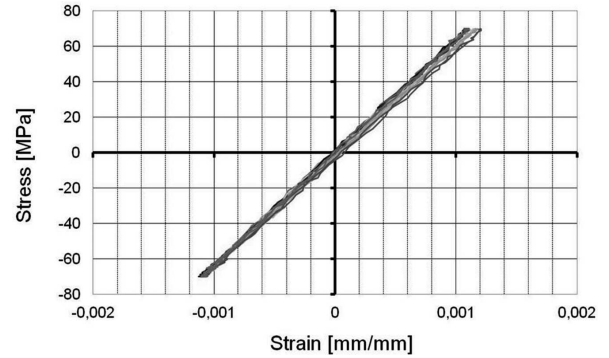

Fig. 8. Hysteresis loops for the cycles over 100 of fatigue tests. Material Al+10%SiC (second series) tested at stress amplitude equal to 70 MPa
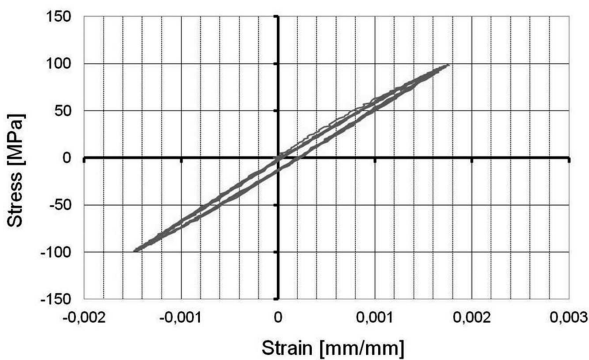

Fig. 9. Hysteresis loops for the initial cycles of fatigue tests. Material Al+2,5%SiC (second series) tested at stress amplitude equal to 100 MPa
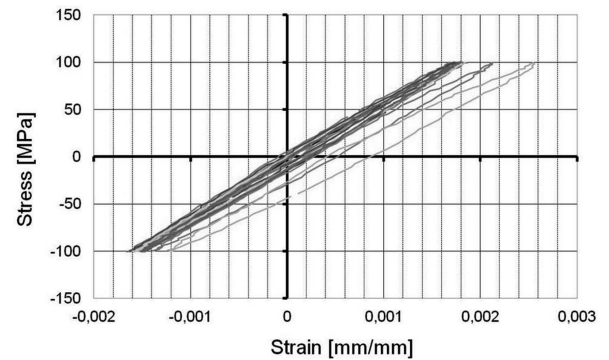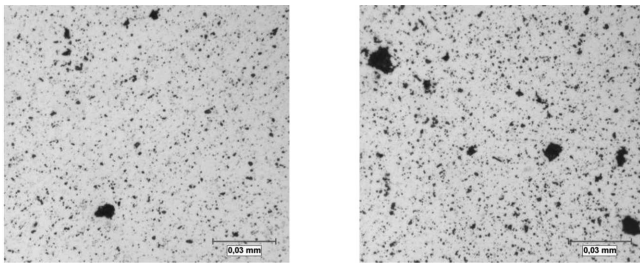

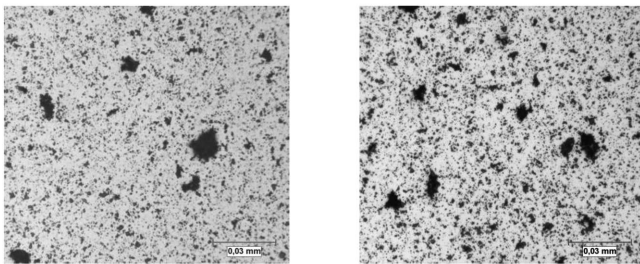Fig. 10. Hysteresis loops for the cycles over 100 of fatigue tests. Material Al+2,5%SiC (second series) tested at stress amplitude equal to 100 MPa

4. Microstructural examination

In the first step of the investigation programme preliminary microstructural observations were carried out before fatigue tests for the first series of Al/SiC composites. Images were taken for the mutually perpendicular cross sections of rods produced using the KOBO method. SiC particles of small sizes uniformly distributed in the composite matrix, as well as SiC particle agglomerates were observed for rods of the first series (Fig. 11). The quantity of SiC agglomerates increases for the higher SiC content. These agglomerates should be treated as microstructural defects and they can be mainly responsible for voids and cracks generation. Moreover they can affect a type of damage mechanism evolution during fatigue tests. An analysis of Al/SiC (first series) microstructure after fatigue tests was presented in the separate paper [8].

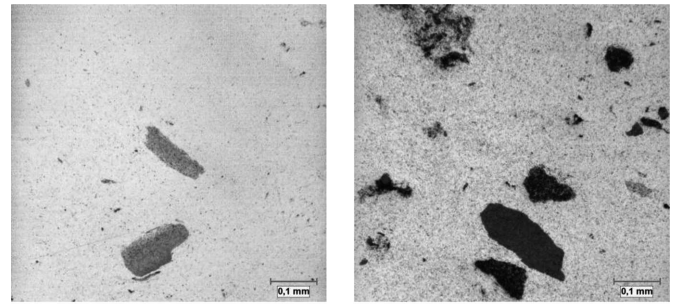a) Al+2,5% SiC, magn. 500x   b) Al+5% SiC, magn. 500x

c) Al+7,5% SiC, magn. 500x   d) Al+10% SiC, magn. 500x

Fig. 11. Images of microstructure: transversal cross sections of Al/SiC composites (first series) before fatigue tests (magn. 500x)

Both transversal and longitudinal cross sections of the second series rods before (Fig. 12, 13) and after fatigue tests (Fig. 14, 15) were taken into account. Non-uniform distribution of SiC particles in the composites examined can be observed for the materials before fatigue tests. A tendency to form SiC agglomerates is stronger for the second series of composites, that it is clearly shown either on transversal or longitudinal cross sections. It is easy to notice that the quantity and size of SiC agglomerates increase with an increase of SiC content in the composites.
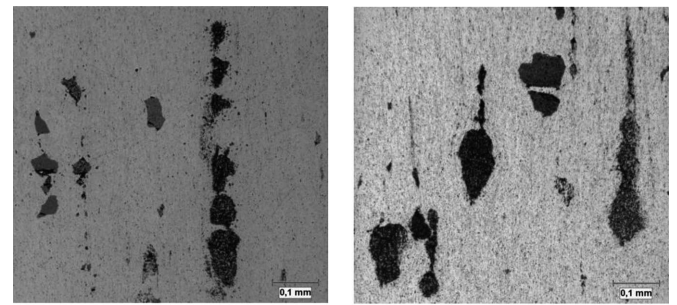
A distribution and orientation of the reinforcing agglomerates formed during composites production, especially visible on the longitudinal cross sections (Fig. 13) may be treated as the main disadvantageous microstructural effect.

Microstructural images observed after fatigue tests for Al/SiC composites (second series – Fig. 14) confirmed such conclusion since the voids and cracks were mainly distributed in places of SiC agglomerates location.
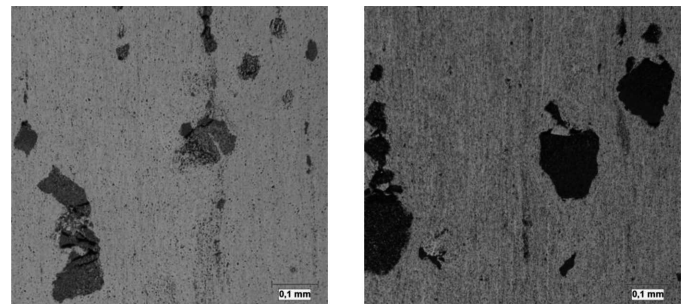

a) Al + 2,5%SiC magn. 100x   b) Al + 10%SiC magn. 100x

Fig. 12. Images of microstructure: transversal cross sections of Al/SiC composites (second series) before fatigue tests (magn. 100x)

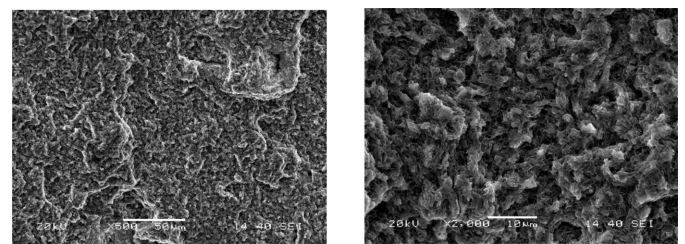a) Al + 2,5%SiC magn. 100x   b) Al + 10%SiC magn. 100x

Fig. 13. Images of microstructure: longitudinal cross sections of Al/SiC composites (second series) before fatigue tests (magn. 100x)

a) Al + 2,5%SiC magn. 100x   b) Al + 10%SiC magn. 100x

Fig. 14. Images of microstructure: longitudinal cross sections of Al/SiC composites (second series) after fatigue tests (magn. 100x)

An analysis of images presenting fracture surfaces after fatigue tests for Al+SiC composites (second series) (Fig. 15) leads to the remark that the fatigue fracture type was observed in majority of tests carried out. Voids and cracks were identified in the fracture areas.

a) magn. 500x   b) magn. 2000x

Fig. 15. Fracture images after fatigue tests for Al+7,5% SiC composite (second series) (SEM)

5. Final remarks

Fatigue damage parameter for the Al/SiC material (first series) was calculated on the basis of mean inelastic strain as a fatigue damage indicator, since the dominant damage mechanism during fatigue tests was ratcheting. The rate of damage was higher at the beginning of tests, which may result in a failure of components made of the composites during the first period of exploitation.

The Al/SiC material (second series) exhibited different damage mechanisms during fatigue tests. Moreover, mean inelastic strain not only increased but also decreased during subsequent cycles. That is why the method based on the modified fatigue damage indicator would be the best tool to evaluate fatigue damage parameter. Unfortunately, it is sensitive to the number of cycles taken into account and so is still under development.

Microstructural observations enabled identification of SiC particle agglomerates that include incoherent particles, which may influence damage mechanisms during fatigue tests. From microstructural point of view they are heterogeneities to a great extent and can be the main reason of voids and cracks initiation and their growth during fatigue process.

Acknowledgements

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