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INFLUENCE OF MODIFICATIONS ON FATIGUE STRENGTH OF AlSi17Cu5Mg(Fe) ALLOY USED FOR PISTONS FOR INTERNAL COMBUSTION ENGINES

Technological progress in construction of automotive vehicles, particularly in construction of engines, enforces simultaneous changes in foundry properties of aluminum alloys used in automotive industry. Until recently, abrasion resistance was the main usability criterion of a material used for pistons for internal combustion engines. At present however, because of the complexity of the process of the fuel mixture combustion, more restrictive standards of limited hydrocarbon emission, and the pursuit of reduction of the vehicle's mass, fatigue strength of silumins enjoys a continuously increasing interest. The paper presents results of a computer simulation using the finite element method (FEM) and a real fatigue test of AlSi17Cu5Mg(0.5Fe) (A390.0) alloy with unilateral variable bending. The tests aimed to simulate a deflection of a combustion engine piston in a cylinder barrel were carried out in two variants: for a non-modified alloy and an alloy modified with CuP10 master alloy. Based on the distribution of stresses according to the Huber-Mises-Hencky theory (for a given range of the deflection from 0.1 to 0.3 mm), Wöhler curve was determined for the studied alloy. Based on on microstructural investigations, cracks of primary Si crystals were found, caused by fatigue changes resulting from unilateral pulsating vibrations.

Keywords: fatigue strength, Al-Si alloys, FEM analysis, Wöhler diagram

1. Introduction

From among all parts of an internal combustion engine, piston is the element most of all exposed to thermal damage. As the only movable element of the combustion chamber, it must be resistant to high temperatures and variable pressures. The pistons are subject to wear: abrasive wear, adhesive wear, corrosive wear, thermal wear, seizing, cavitation wear, and fatigue wear [1]. In the result of so variable operating conditions, vibrations occur, caused by dynamic loads having a character of impacts occurring in the moment of the change of the piston's lateral position. It leads to a significant increase in stresses in the cylinder and its vibrations, responsible, among others, for the level of noise generated by the internal combustion engine. Therefore, car manufacturers search for new design and material solutions, which would rise to the challenge of the constantly increasing requirements. Al-Si foundry alloys called silumins are one of such materials used in the automotive industry [2]. They are materials characterized by high performance, physical and mechanical properties, dimensional stability, corrosion resistance and good thermal conduction. So favorable relation of properties results from optimum primary structure of silumins, formed by dendrites of α(Al) solutions with various shares of eutectoids and β(Si) crystals [3]. In hypereutectic silumins, morphology of these crystals, crystallizing as primary crystals, is quite diversified, which results from their uncontrolled nucleation and growth. Such crystallization leads to flat platelets with sharp edges, being a result of specificity of the mechanism of planes' growth in expanding silicon. It leads to formation of multipointed crystals with star structure on the substrate of a heterogeneous nucleus [4-7]. The so-formed coarse crystalline structure, consisting of, among others, brittle primary silicon crystals, affects the performance unfavorably, particularly machinability of silumin casts, which is a large hindrance in case of pistons. Thus, the process of modification of silumins becomes necessary, which in the case of hypereutectic alloys, is aimed for a reduction in size of primary silicon crystals (from approx. 1 mm to less than 50 μm), their uniform distribution in the matrix of the α(Al) solutions, and a change of the unfavorable eutetics form from lamellar to fibrous one [8-11]. For this alloy group, master alloys based on phosphorus (CuP, AlSiP, AlZrP) [12-14] or phosphorus penta- or trichlorides [7,8] are the most frequently used modifiers. Efficiency of refinement of the primary structure (apart from a modification) may be improved also by a proper selection of chemical composition of batch materials with a known history of production [15]. However, the research carried out indicates that in spite of abiding by the technological regimes, correct solidification process, and optimum chemical composition,

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development of microcracks occurs in case of fatigue wear of silumins, often leading to the piston damage. Therefore, studies are carried out on improvement of Al-Si foundry alloys, in order for the obtained material to be resistant to fatigue wear too [16].

Verification of performance of the obtained materials is being carried out experimentally, as well as model tests. Experimental tests are expensive, because they require production of prototype casts and their testing by, usually expensive, measurement & testing equipment, and also significant time [17]. Every material change being introduced forces application of new specimens for the tests, additionally increasing the cost of the operation because of the fact that the preparatory works are more time-consuming. Thus, model testing is frequently used in the initial phase of material studies. It allows for shortening of the time used for the tests by application of virtual models for analyses of various types, contributing into a reduction of costs of new prototypes, and particularly those of determination of optimum parameters assumed during the tests. It pertains to e.g. the deflection value during actual fatigue tests of light aluminum-based alloys obtained by various casting techniques [18].

2. Aim and scope of the studies

The aim of the paper is to present the results of a computer simulation using the finite element method (FEM) and an actual fatigue test of the AlSi17Cu5Mg(Fe) alloy in a non-modified state (designation: material A) and after modification with CuP10 master alloy (designation: material B). The aim of the paper assumes also determination of optimum deflection value content during unilateral pulsating loads under simple bending.

In order to achieve the assumed goal, the scope of works included:

- FEM analysis and distribution of stresses according to the Huber-Mises-Hencky theory for deflections of 0.1, 0.2, and 0.3 mm;
- actual fatigue tests under laboratory conditions;
- microstructural tests.

3. Material and methodology

AlSi17Cu5Mg(Fe) silumin was selected for tests. It is an alloy from A3XX.X (A390.0) series intended for casting in sand molds and metals molds. This alloy, developed by NASA, was intended initially for rocket operation at temperatures from 230°C to 400°C [19]. However, as the regulations on limited emissions became more stringent and mechanical properties, good dimensional and tribologic stability increased, it found common application in many branches of the civil sector, particularly in automotive industry for, among others, pistons and heads of high-loaded internal combustion engines.

The selected silumin was smelted from EN AM-AlSi20 alloy (acc. to PN-EN 575), pure aluminum (acc. to PN-EN 576), and AlCu30 and AlMg10 master alloys (acc. to PN-EN 575). The alloy was melted in a VSG 02/631 Balzers induction vacuum furnace in a SiC crucible with a capacity of 800 cm^3, according to the technique described in [15]. After obtaining the required technological parameters (temperature and time), the alloy was subjected to modification with CuP10 master alloy (ca. 9.95% by wt. P) at a temperature of 840°C. 0.2% by wt. of the master alloy was added, amounting to approx. 170 ppm in conversion to the phosphorus content in the alloy. After a defined time, the alloy was refined using Rafglin-3 preparation in an amount of 0.2% by wt. After the formed slag was removed, the alloy was cast from the temperature of 830°C to a metal mold (acc. to PN-65/H-88003), obtaining a cooling rate of approx. 14°C$\cdot$s^{-1}, from which samples for fatigue tests were obtained. Towards the end of casting, an additional sample was collected for the chemical composition determination (by a Foundry Master Compact 01L00113 emission optical spectrometer). Also, microsections for microstructural observations were prepared from these samples. Metallographic tests were carried out using an MeF-2 optical microscope, and X-ray microanalysis – using a Hitachi S-4200 scanning microscope with an EDS Voyager spectrometer from Noran.

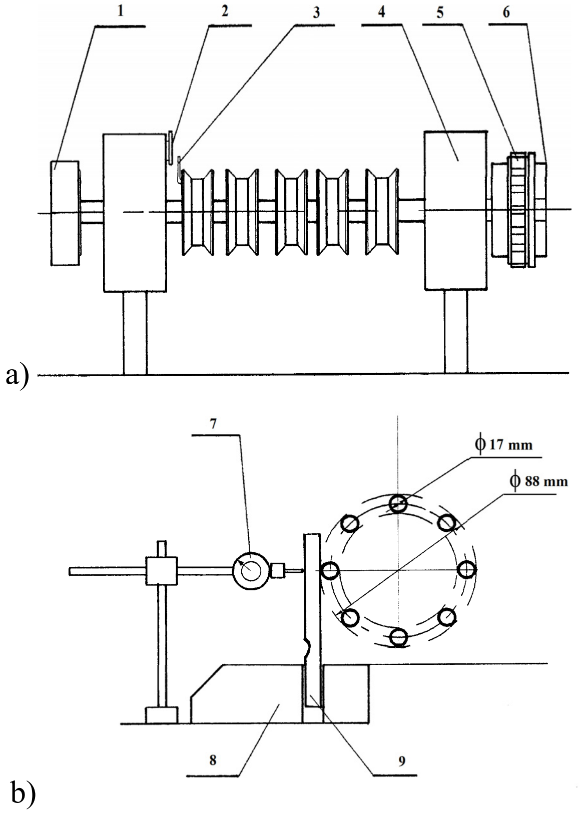

Fig. 1. Loading mechanism: a) side view, b) front view; 1 – sheave with a V-belt, 2 – revolution measurement sensor, 3 – auxiliary part for the measurement sensor, 4 – main shaft bearing mount, 5 – bearing rings with rollers, 6 – fixing screw for the internal part of the bearing, 7 – dial gauge, 8 – vice, 9 – sample

In future, the selected material is to be intended for pistons for internal combustion engines. Therefore, the studies were aimed to represent the impact of the force of gases formed during the combustion on the piston head. The fatigue tests consisted in subjecting the material to unilateral pulsating loads during simple bending. For this purpose, a fatigue tester for unilateral pulsating tests in the Department of Automotive Vehicle Service of the Faculty of Transport, Silesian University of Technology, shown in Figure 1, was used.

The loading mechanism is to create the assumed periodically time-variable stresses in the sample. This task is realized by defining a proper deflection, affecting the tested sample. Shape and dimensions of the sample for fatigue tests are shown in Figure 2.

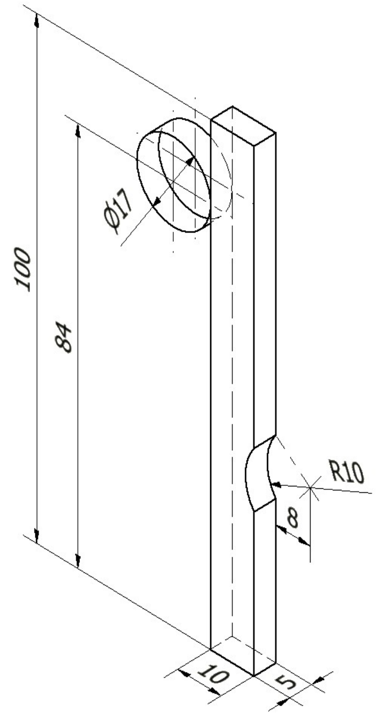

Fig. 2. Dimensions of the sample and the guide roll

The size of the sample deformation may be adjusted by corresponding movement of the sliding jaws of the vice. After the sample is fixed, the deflection value should be read on the dial gauge, being a direct measure of the stresses affecting the sample. Thanks to the fact that the tester is equipped with an electronic sensor counting the number of revolutions of the shaft, the number of cycles accompanying the test may be calculated. Elements having a direct contact with the tested sample rotate around their axis, so friction between them and the sample is very low, and the test occurs practically at a one-time simple bending. The sample is fatigued till it fractures or an adequate number of cycles is reached, after which the sample will not fracture. The number of cycles is obtained from the product of the number of revolutions and the number of rolling elements of the bearing. So far, the fatigue tester was used for testing iron alloys, where the deflection was in the range from 0.7 to 0.9 mm. In case of Al alloys, the forces are significantly lower, and preliminary calculations indicated the deflection values at the level of 0.2 mm. In this connection, the bearing was replaced and calibration of the main driving shaft was carried out so as to the deflection span on the individual rolls did not exceed 5%. Also, an additional sensor was installed, enabling measurements of the deflection value.

The main problem during fatigue tests of Al-Si alloys consists in a necessity of an exact determination of the deflection (stresses) resulting from their low deformability. Even a slight transgression (at a level of 0.1 mm) of the assumed values leads to immediate fracture of the sample and precludes testing. The standard procedure for determination of the deflection using the dependence [20] was inadequate in this case, because of too low precisions. In order to increase the precision of calculations and determine the testing parameters, FEM analysis was carried out.

4. FEM analysis

A fatigue tester model consists of a pressure roll and the tested sample made of the selected material. The pressure roll was modeled as a discrete rigid surface. The sample having the assumed material parameters, such as Young modulus, Poisson ratio, density and the data considering the material plasticity was prepared using 3D technique. The material data pertaining to its density and plasticity were obtained by experimental testing [15]. In the fixing spot of the sample in the vice, beam elements of MPC-type were used, connecting the control point, in which all degrees of freedom were removed, with the side walls of the sample adhering to the vice. Between the surface of the pressure roll and the sample surface, elements enabling contact mating of the surface-surface type, considering the friction between the mentioned surfaces, were used. For Al-Si alloys, the coefficient was assumed as $\mu = 0.3$. The assembly consists of 1070 surface elements of the R3D4 type: A 4-node 3-D bilinear rigid quadrilateral for the roll and 38190 elements of the C3D8 type: An 8-node linear brick for the sample [21].

Chemical composition of the AlSi17Cu5Mg(Fe) alloy is shown in Table 1.

5. Results of simulation tests

Figs. 3-5 present the results of the analysis of simulation tests for the AlSi17Cu5Mg(Fe) silumin in non-modified state (material A) and after modification with CuP (material B). For the needs of the simulations, the Huber-Mises-Hencky theory

TABLE 1

Chemical composition of the AlSi17Cu5Mg(Fe) alloy (% by wt.)

Alloy	Si	Cu	Mg	Ni	Mn	Fe	Cr	Zn	Pb	Ti	Other
A390.0	16.34	4.56	0.88	0.02	0.03	0.46	0.02	0.01	0.01	0.03	0.05

was used, according to which a material is transformed into plastic state in a given point, when the density of strain energy of distortion (i.e. deviator energy) reaches a boundary value, characteristic for this material.

The obtained simulation results show differences between the non-modified silumin and the modified silumin. For all deflections, the stresses for the non-modified alloy were higher that in the case of the material modified with CuP10. For the deflection of 0.1 mm, the maximum stress value amounted to 55.6 MPa for the non-modified alloy, while for the modified material, it was lower by 16.5 MPa and amounted to 39.1 MPa. In the case of the deflection of 0.2 mm, the maximum stress value for the material modified with CuP10 master alloy was calculated as equal to 72.4 MPa, while for the non-modified silumin, it amounted to 89.6 MPa and was higher by 17.2 MPa. In the case of the deflection of 0.3 mm, the maximum stress value for the non-modified material exceeded 100 MPa and was at the level of 114.4 MPa, while for the modified material the maximum stress value was obtained equal to 93.8 MPa and it was lower by 20.6 MPa. The obtained results indicate also that the increase in the deflection value is accompanied by an increase in the difference between the materials, proving the significance of the process of modification of the tested silumin with CuP10 master alloy. Moreover, it should be emphasized that the obtained values pertain to dynamic deformation of the material, and the obtained values of maximum stresses will be lower than those obtained in the case of a static tensile test [15].

6. Results of laboratory tests

Considering the mechanical properties of the studied alloy, including Rm at the level of 210 MPa, and the earlier FEM simulations, it was necessary to set a very small initial deflection at the level of 0.1 mm, both for material A, and B. With the given deflection, the studied samples were not fractured and no traces of cracks were visible, and the test was discontinued after obtaining 107 bends. The difference between materials A and B became visible for the deflection value of 0.2 mm. The non-modified alloy withstood approx. 3500000 bends, whole the silumin after modification with CuP10 withstood 5000000 cycles. In Figure 6, microcracks, which occurred in the area of the highest impact of the bending forces are shown. In the case of the non-modified alloy, the cracks have a more widespread character and there are more of them while compared to the alloy after modification.

Under the influence of the bending forces, the forming microcracks encompass not only the matrix area (solid solution α), but also primary precipitations of silicon. At the deflection value of 0.2 mm, cracks of primary silicon crystals were observed, forming in the areas of the highest impact of the bending forces, shown in Figure 7. Characteristic sports have been selected, which show that for the A390.0 alloy (non-modified and after modification), the cracks resulting from the impact of the bending forces penetrate the silicon crystal and do not run along its edges.

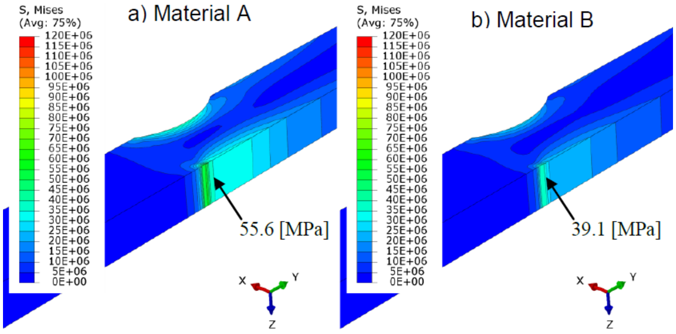

Fig. 3. Stress map according to the Huber-Mises-Hencky theory for the deflection of 0.1 mm

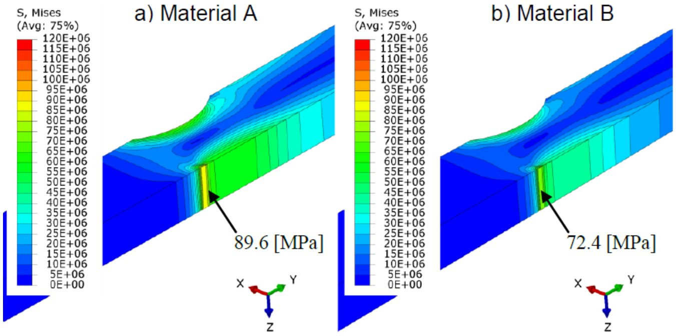

Fig. 4. Stress map according to the Huber-Mises-Hencky theory for the deflection of 0.2 mm

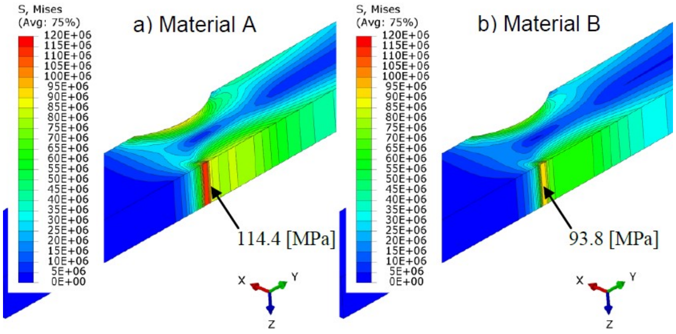

Fig. 5. Stress map according to the Huber-Mises-Hencky theory for the deflection of 0.3 mm

While using the deflection of 0.3 mm, material A cracked after 1250000 bends, while material B – after 2800000 bends. These results proved unequivocally that the non-modified silumin has a worse fatigue strength (by more than 50%) than the modified silumin. Summary of number of cycles (bends) for the three selected deflection values are shown in Tab. 2.

Figure 8 shows the cracked surface of the studied silumin sample. These cracks, both in the case of the non-modified alloy, and the modified alloy have a non-uniform character. They run both along the edges of the silicon crystals and on their surfaces. A similar type of cracks was observed at the deflection value of 0.2 mm.

Figure 9 shows the Wöhler diagram of the obtained results of fatigue tests for the AlSi17Cu5Mg(Fe) alloy in the non-

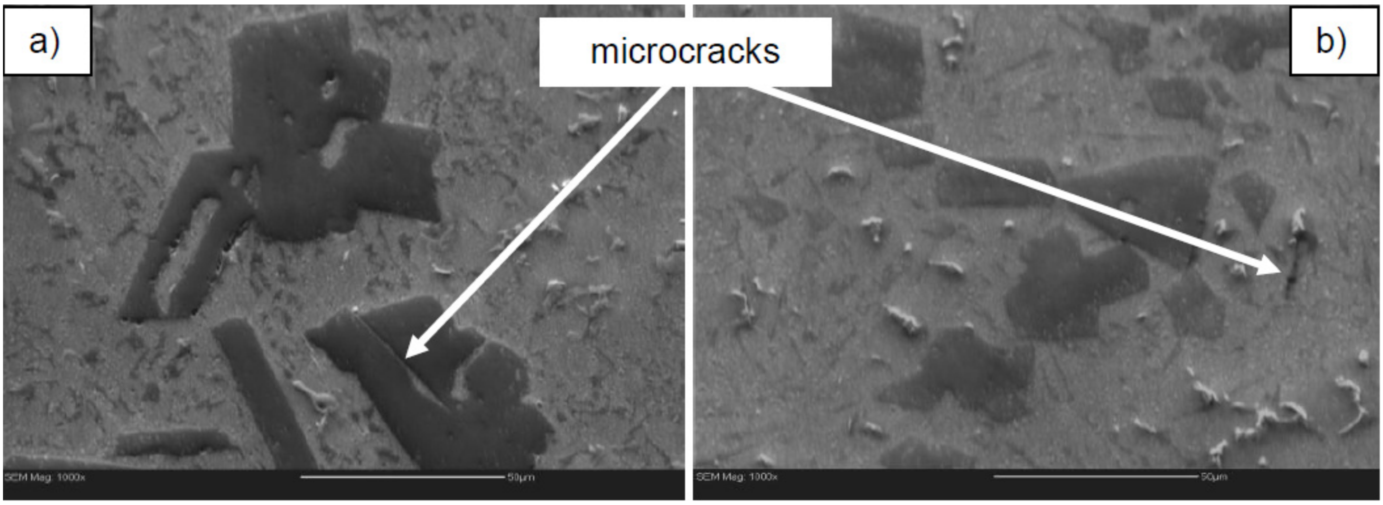

Fig. 6. Microcracks of the AlSi17Cu5Mg(Fe) alloy: a) non-modified state, b) after modification with CuP10 master alloy

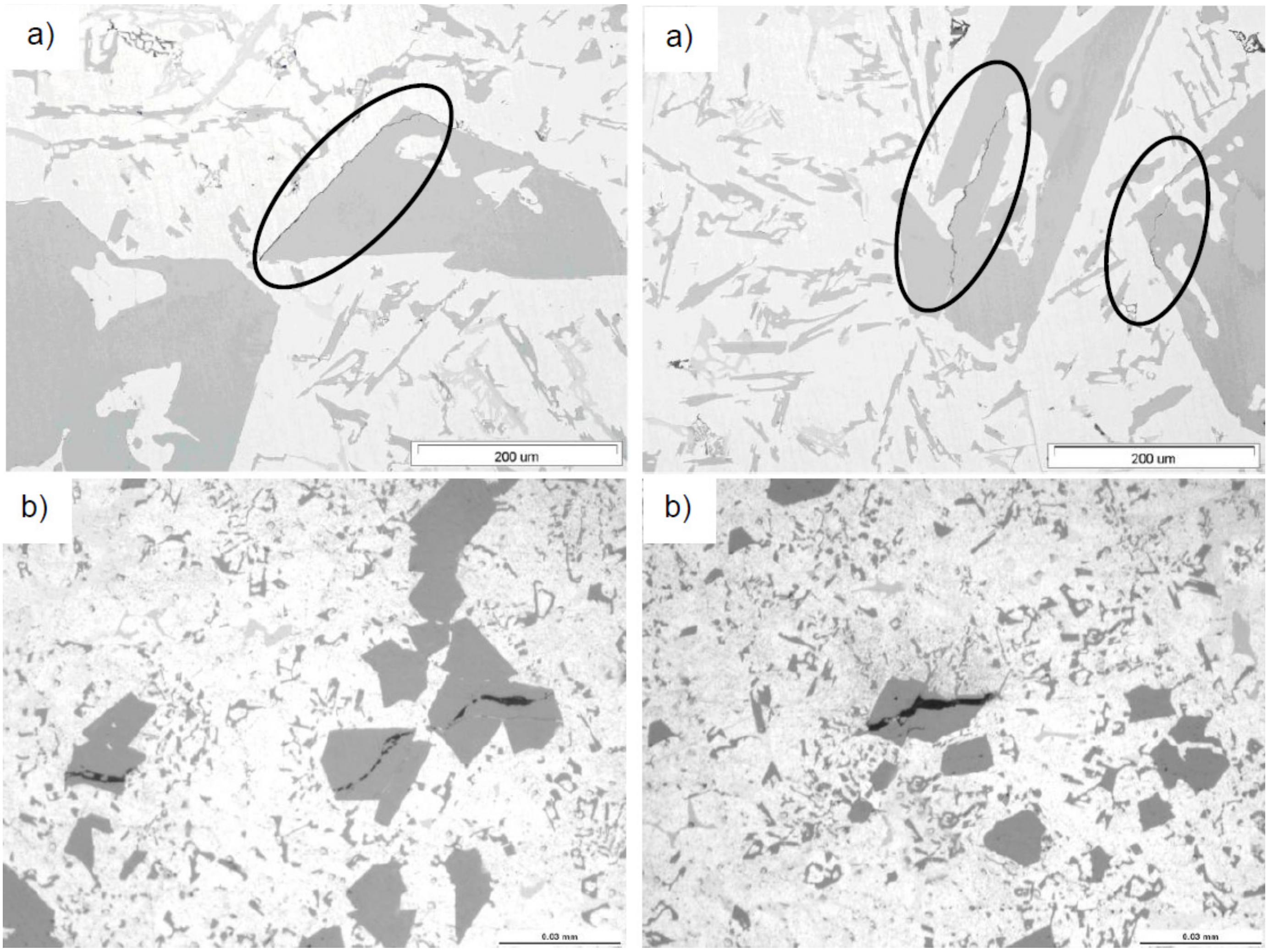

Fig. 7. Cracks of primary silicon crystals caused by the impact of unilateral pulsating vibrations in the AlSi17Cu5Mg(Fe) alloy: a) non-modified state, b) after modification with CuP10 master alloy

modified state (material A) and after modification with CuP10 master alloy (material B).

The presented results show a difference between the AlSi17Cu5Mg(Fe) alloy cast in its non-modified state and after modification with CuP10 master alloy. Simultaneously, variable locations of the curves indicate the influence of the modification of the studied silumin on its fatigue strength. The higher the deflection value of the material, illustrating also the operation of

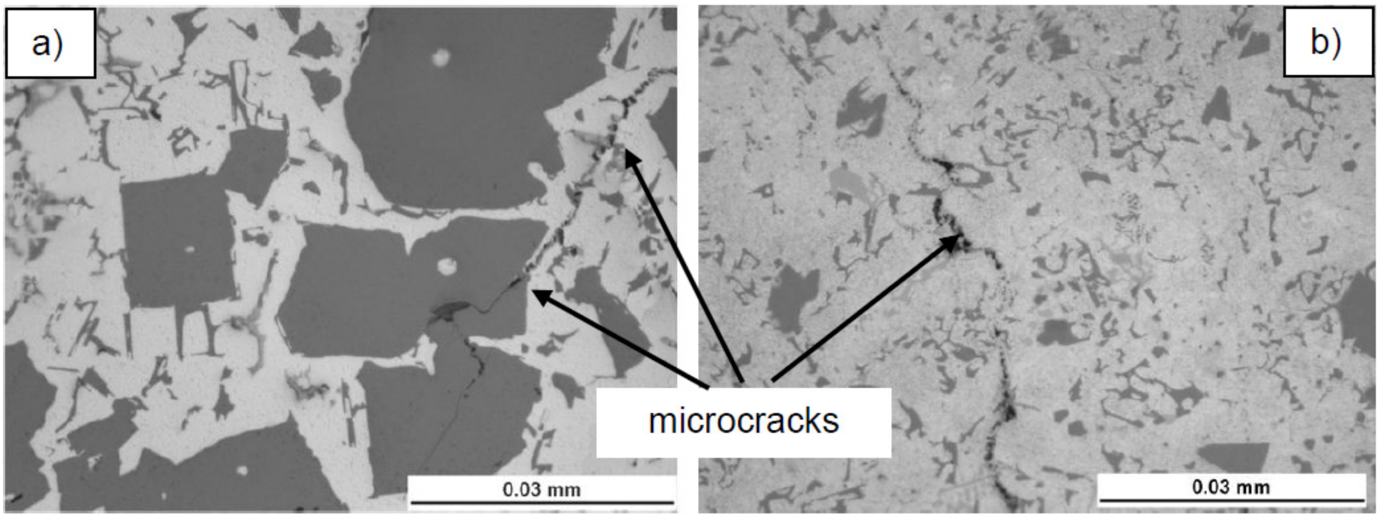

Fig. 8. Total fracture of the sample at the deflection value of 0.3 mm: a) material A, b) material B

TABLE 2

Number of bends depending on the deflection value of the AlSi17Cu5Mg(Fe) alloy

Deflection value, mm	Number of bends		Difference between A and B	Condition of the material after the test
	Material A	Material B		
0.1	10000000	10000000	0	material did not cracked
0.2	3500000	5000000	increase by 43%	crack of the material
0.3	1250000	2800000	increase by 124%	crack of the material

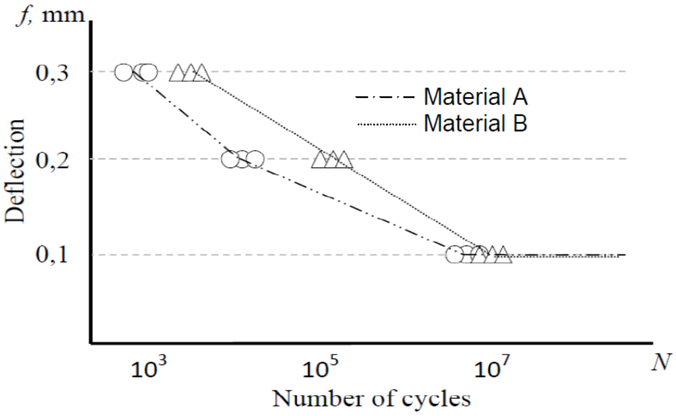

Fig. 9. Wöhler diagram for the AlSi17Cu5Mg(Fe) alloy for the non-modified state (material A) and after modification with CuP10 master alloy (material B)

an internal combustion engine's piston, the higher the difference between the modified and non-modified alloy. The difference is even more evident for the deflection value of 0.3 mm.

7. Summary

Based on FEM simulation and actual tests of the fatigue process in the area of the highest impact of the bending forces in the result of unilateral pulsating vibrations, it may be concluded that at the deflection value less than or equal to 0.1 mm, the silumin does not yield to fatigue wear. During the tests, it was found also that for the deflection value higher than 0.4 mm, fracture of the AlSi17Cu5Mg(Fe) alloy sample occurs immediately, already after 20 bends. The obtained results show that silumin modified with CuP10 may be used for pistons pistons for internal combustion engines with power up to 100 kW, where no deflection higher than 0.1 mm occurs [22]. However, in the case of high-loaded engines (transport vehicles, Diesel engines) or sport engines, the material is unsuitable because of its too low fatigue strength. On the other hand, the alloy in its non-modified state cannot be used practically for piston casts because of its low fatigue strength.

It should be emphasized that the realized tests are hard to carry out because of a high brittleness of the A390.0 alloy, requiring a very precise positioning of the deflection and its continuous keeping during a test. Also, an adequately long testing process is necessary, as too short periods will result in rapid fracturing of the sample without evident changes in the structure of the studied material.

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