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Fatigue Resistance of A390.0 Alloy Modified with Phosphorus

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Abstract

The paper presents fatigue tests (unilateral pulsating vibrations) for hypereutectic silumin AlSi17Cu5Mg aimed at simulation of deflection of the piston head in a combustion engine. The methodology of the tests and the way of marking the deflection of the tested material is described together with the detailed description of the test stand. The fatigue resistance Z_G was identified in the tested material and a Wöhler diagram was prepared to show the areas of limited and unlimited fatigue resistance.

Keywords: Fatigue wear, Unilateral pulsating vibrations, Hypereutectic alloy Al-Si

1. Introduction

Increase of operational reliability causes that attention has been turned to elements of machines which are subject to damage by stress which are far smaller than the emergency resistance of the given material which was marked in static tests. It was stated that crackings occur without any noticeable plastic deformations and are connected with the viability of the working element by changeable stresses [1-4].

Fatigue wear is a type of wear in which the sectional loss of cohesion and losses in material connected with it are caused by material fatigue due to cyclic influence of contact stresses in surface layers as well as associated friction components. It should be remembered that the surface fatigue wear is different from volume fatigue wear. The results of processes of surface wear are local losses of material in the surface layer whereas in case of volume fatigue wear the fatigue crackings appear.

There are also different reasons why the fatigue wear begins, resulting from different character of the strain. In case of the surface fatigue wear they are contact-type stresses [2-4]. In case of volume fatigue wear they result from many macroscopic elastic deformations and the surface fatigue crackings appear during friction, usually under the influence of multiple deformations of elastic-plastic or plastic type. Also, in both cases the conditions of material strains which lead to fatigue decohesion are different [3].

2. Aim and scope of tests

The aim of the paper is to present the methodology of fatigue test and determination of fatigue resistance ZG for unilateral pulsating vibrations which show the real deflection of the piston head in a combustion engine for alloy AlSi17Cu5Mg. The alloy chosen for test was one modified with phosphorus (CuP10).

In order to achieve the assumed aim, the paper includes the following aspects:

- construction of the test stand for unilateral pulsating vibrations,
- methodology of marking the deflection level,
- analysis of the achieved results,

– drawing the Wöhler curve for the tested alloy.

3. Test methodology

Tested samples were influenced by the unilateral pulsating loads during simple bending on fatigue machine which is shown in figure 1. Main elements of the machine are attached to the table 11: three-phase engine 7 which powers the machine, mechanism of sample load 4. Engine is powered from three-phase network by a steering device (inverter) which allows for smooth control of its rotational speed. The mechanism of load is powered by engine 7 by means of belt transmission (with vee belt). Among supporting equipment there are: revolution counter 6, dial indicator 3 to measure the deflection, vice 9 which jigs the sample 10 and the inverter 1.

The main part of the mechanism which applies load on the sample is the main shaft which is fixed on two bearing mountings. Next, there are wheels for transmission press (which powers the mechanism) and the inner race of the bearing with rolling cylinders (which have direct contact with tested sample) fixed on the shaft.

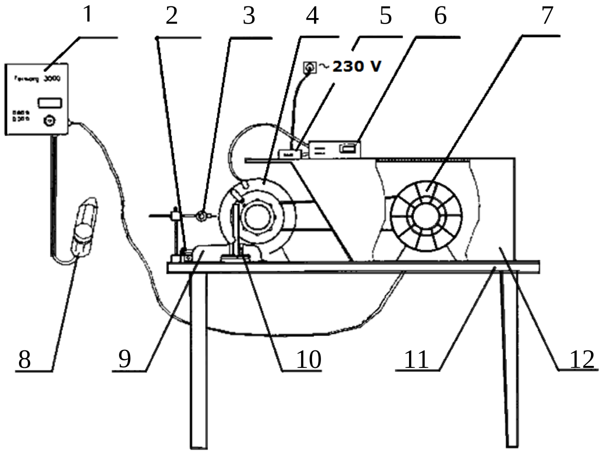

Fig. 1. The outer look of the fatigue machine [4]

The role of the load mechanism is to create in the sample the assumed variable stress periodically in the course of time. This task is conducted by determination of the right deflection under the influence of which the sample remains. The size of sample deformation can be regulated by the proper adjustment of the vice which fixes the sample. The number of cycles which occur in the test can be easily calculated thanks to the fact that the machine has the electronic sensor which counts the number of the rotations of shaft [4]. Elements which have direct contact with tested sample rotate round own axis of revolution and that is why it can be stated that friction between them and the sample is small and the test occurs practically with clean single bend. The system in which the test was conducted is presented in figure 2. Samples for tests of fatigue wear are fixed in such a way that the cut in the sample sticks out 1.2mm above the fixing vice. Next a mark is done on the height of the shaft axis of the machine which marks the place of deflection measurement. The right deflections are set with corresponding bending stresses which are calculated from the formula (4).

After reading the value of deflection (on dial gauge) the force P is calculated together with calculation of stresses which are applied on the sample. For the presented model in fig.2 the deflection is calculated from the equation [5]:

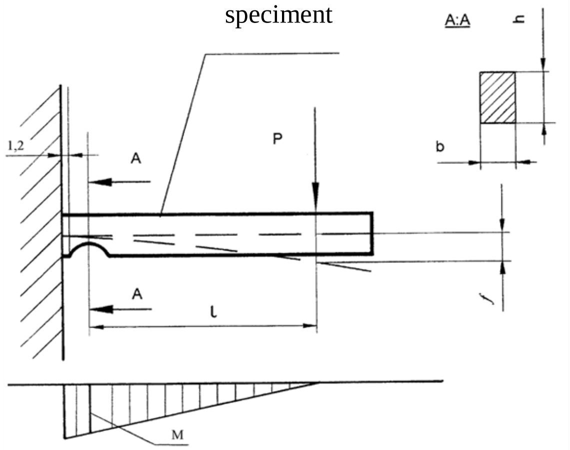

Fig. 2. Test arrangement and the diagram of the bending moment [4]

$$f = \frac{Pl^3}{3EJ} \tag{1}$$

where:
P – force (sample load) [N],
f – deflection (read from dial gauge) [m],
l – arm of a force (measured with slide caliper) [m],
E – Young module (for steel E = 2.1 · 105 MPa),
J – moment of inertia (formula 2).

$$J = \frac{bh^3}{12} \ [\mathrm{m}^4] \tag{2}$$

where:
b and h – respectively breadth and height of the sample [m], (fig. 2).

By mathematic transformation of formulas (1) and (2) the force can be achieved:

$$P = \frac{f3E\frac{bh^3}{12}}{l^3} \tag{3}$$

Next step is calculation of the bending stresses:

$$\sigma = \frac{M}{W} = \frac{6 \cdot Pl}{bh^2} = \frac{3Ehf}{2l^2} \tag{4}$$

where:
σ – bending stress [MPa],
M = P · l – bending moment [Nm],

W – resistance indicator of the resistance of the sample with orthogonal cross-section to bending [m3],
P – load force [N],
l – arm of a load force (Fig. 2).

The sample is undergoing fatigue tests until it breaks or reaches the right number of cycles after which the sample would not crack. The number of cycles is achieved from the product of number of rotations and the number of rolling elements of a bearing in accordance with a formula:

$$N = k \cdot p \tag{5}$$

where:
N – number of cycles,
k – number of shaft rotations read from the counter,
p – number of rolling elements of a bearing (p = 12).

It gives the number of cycles which the sample can resist before it breaks. Results of the tests will be shown on the fatigue diagram.

4. Test material

Tests were conducted on hypereutectic silumin AlSi17Cu5Mg, similar to series A3XX.X type A390.0 for casting in sand moulds and casting dies, meant for casting of rotary pistons of combustion engines, for cylinder compressor blocks and frames, for pumps and brakes. Modification with phosphorus in the amount of 0.05% mass was conducted with the use of key metal CuP10. Refining was conducted with the use of formulation Rafglin-3 in the amount of 0.3% mass. Technologies of hypereutectic alloys preparation with the addition of Cu, Ni and Mg were shown in papers [6, 7]. Metallographic tests were conducted on light microscope MeF-2 Reichert. Metallographic microsections were conducted according to a standard procedure..

5. Analysis of results

Coarse-grained structure has very negative influence on mechanical properties and the ability to mechanical treatment of the castings. Due to that fact the key role in the application of Al-Si alloys in industry is the refinement of the structure, in particular in order to decrease the grain size and to distribute the primary Si crystals evenly in the solution matrix α(Al). This can also be done by modification which results in creating of bigger number of „bases" for heterogeneous nucleation of silicon crystals. The main and the oldest modifier of hypereutectic silumins is phosphorus added in the form of phosphor copper (CuP10), pentachloride or trichloride of phosphorus with different contents of it. As a result of modification with phosphorus a reduction of precipitation occurs (from about 600 to 800 μm) to about 50 μm and their even distribution in alloy matrix [8].

Because of mechanical properties of tested alloy AlSi17Cu5Mg, including *Rm* on the level of 210 MPa, it was necessary to set the very small deflection on the level of 0.1mm. With such parameters the tested sample was not broken and the tests were stopped after achievement of 10^7 deflexions. During tests by deflection level of 0.2mm, after a number of 3 500 000 deflections some micro-crackings were observed in the area of the biggest influence of bending forces.

Figure 4 presents the view from scanning microscope presenting the micro-cracking of AlSi17Cu5Mg alloy.

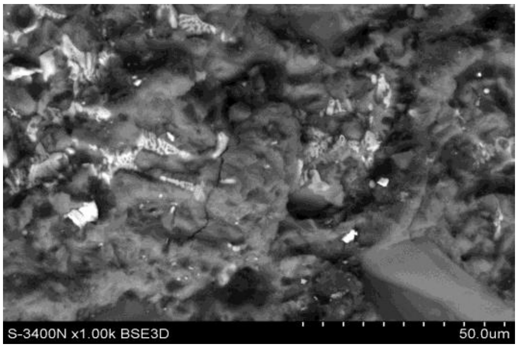

Fig. 4. Micro-cracking of tested sample

Micro-crackings get bigger under the influence of forces in action and if they are not stopped, crackings continue and go to neighbouring grains and take up bigger and bigger areas. Such situation is shown in fig.5. We can observe on the example of microstructures on fig. 5 how the following crystals of silicon start cracking in tested conditions arising after 5 000 000 deflections with deflection level of 0.2mm. Cracking of the whole sample occurred after 6 500 000 deflections, where micro-crackings of particular crystals of silicon joined into one which is shown in fig.6.

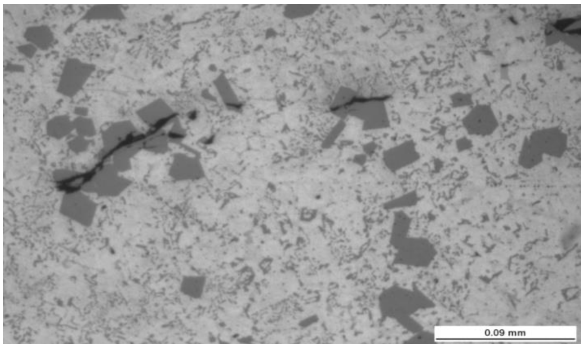

Fig. 5. Crackings of silicon crystals caused by unilateral pulsating vibrations

Fig. 6. Total cracking of sample by deflection of 0.2 mm

By deflection level of 0.3mm after 3 000 000 deflections a total cracking of sample occurred and it can be seen in fig. 7. Achieved Wöhler diagram is shown in Fig. 8.

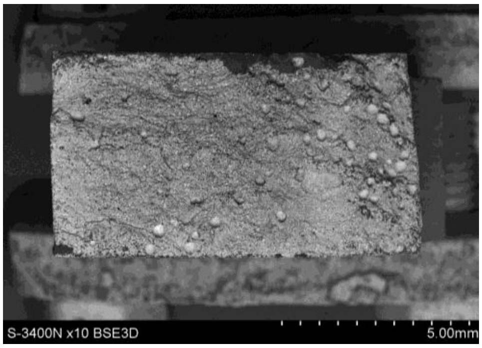

Fig. 7. View of surface of cracked sample with deflection of 0.3 mm

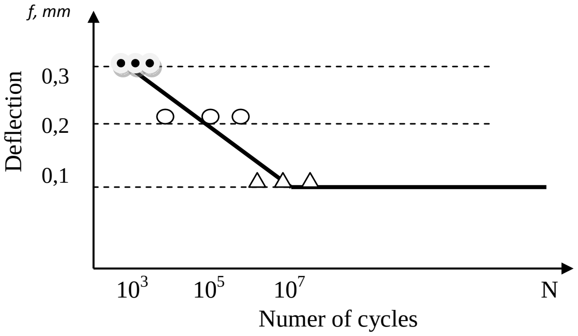

Fig. 8. Wöhler diagram for AlSi17Cu5Mg alloy

5. Summary

The mechanism of decreasing the resistance of material by changeable loads occurs due to the fact that no material has perfect construction, there is no material which is fully homogeneous or isotropic. It can include gas bubbles, non-metallic inclusions, deformations of crystalline structure etc. Besides, on the surface of the element some mechanical damages can appear, i.e. carbon formations. That is why, even if a stress occurs in reference to the whole element produced from a given material and it does not exceed the elastic limit, it does happen that the stress can exceed the elastic limit in areas which are additionally weakened.

It should be underlined that conducted tests are difficult to perform due to brittleness of tested alloy AlSi17Cu5Mg and it is necessary to apply small bending forces and high precision of setting the deflection level.

It refers to a situation in which a necessity arises to acknowledge the process of material fatigue and therefore a long research process is needed. Short periods of fatigue tests led to quick cracking of sample without the visible changes in structure arising as a result of forces applied on them. It is also difficult to notice the moment when the visible fatigue (a change in structure) occurs because the tests are conducted on alloy which was not earlier analysed with the use of this method.

On the basis of simplified Wöhler diagram presented in figure 8 it can be concluded that with deflection level lower than 0.1mm the material does not show any fatigue use. By deflection level from 0.4mm the cracking of sample occurs immediately, that is after about 20-25deflections. Achieved results show that the tested material can be applied on pistons of combustion engines with motor rating up to 100kW where the values of material deflection do not exceed the level of 0.1mm. However, in case of modern sports engines where pistons with variable geometry of shape are applied, the fatigue resistance of tested alloy is not sufficient.

Applied methodology and devices allowed to show that it is possible to mark the fatigue resistance for tested alloy AlSi17Cu5Mg after modification with phosphorus. The tests are also a supplement for the measurements of friction force of the analysed material. It is necessary to determine the fatigue wear for tested alloy depending on different technological history.

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