1. Introduction

Mg-alloys are known as materials with high specific strength and damping capacity. They have also good castability and are easy to recycle. Recently, they attract increased attention as possible structural material in aerospace and automotive industries [1]. Of course, their limited ductility, easy oxidation and relatively low ultimate strength, constrain for now, their wide applications. Researches of Mg-alloys concentrate their investigations mainly on the following topics: corrosion resistance [2, 3, 4, 5]; creep resistance [6, 7, 8], and fatigue life durability [9, 10, 11, 12, 13,14]. Among Mg-alloys AZ91 is one of the most used (more than 50% of all Mg-alloys). The aim of the current investigation is to obtain fatigue endurance strength of this alloy on a base of $10^8$ cycles and to analyze broken surfaces.

For light metals, it is known that there is no true fatigue limit. However, the fatigue life of current automobile engines ranges around $10^8$ cycles, around $10^9$ or even $10^{10}$ cycles are in interest for turbine engine components [10,15]. Such experiments for conventional fatigue machines are very time consuming, but if ultrasonic fatigue testing at frequency 20kHz is used, $10^8$ cycles can be reached in about two hours.

2. Ultrasonic fatigue testing and equipment

To develop high stresses in the tested specimen ultrasonic fatigue testing requires cycle loading at its resonance frequency. For this purpose all vibrating parts of the testing machine, as well as the specimen, have to be designed with appropriate shape and dimensions.

Ultrasonic fatigue machines usually have three main systems: an ultrasonic system, which consists of a generator, a piezoceramic transducer, an amplification unit, and a specimen and supply resonance mode vibrations at 20kHz; a measuring and control system for measuring vibration amplitudes, cycles counting and a generator “on-off” control; additional systems like a cooling device, a crack growth measurement device, etc.

Ultrasonic system

Scheme of ultrasonic system of testing machine, designed in TU-Varna is shown on fig.1 [16] The generator (1) delivers high voltage sinusoidal signal to the piezoceramic transducer (2), which converts the electrical signal to mechanical vibrations. Both devices are commercially available from MPI-Switzerland, designed for ultrasonic welding, but fit well the requirements of fatigue testing [17]. The generator can deliver 1kW power in a wide frequency range (15-100kHz). The transducer with power up to 3kW, has working (resonance) frequency 20±0.5kHz and can produce maximum peak-to-peak amplitude 20μm. The ultrasonic generator has closed loop control of supplied voltage and frequency in order to keep the resonance conditions and the constant vibration amplitude. The vibrations of the transducer are amplified by a booster (3) and a sonotrode (4). The booster have amplification ratio 1:1.5, resonance frequency around 20kHz and is made of Ti6Al4V-alloy. It’s designed with a wide flap in nodal plane for fixing the whole system. The sonotrode has a conical shape with amplification ratio around 1:3 and is made of Al7075-T6 alloy [18]. Symmetrical specimens with stress concentrator in the middle (hourglass or dumbbell) have to be designed. The length of the specimen is calculated from the half wave ($\lambda/2$) condition [19] i.e. center of the specimen is displacement node and ends are displacement antinodes, fig.1.

Measurement system

The measurement system consists of a displacement sensor and a thermocouple. NI cDAQ chassis with 9211, 9215, and 9401 modules is used for data acquisition.

The displacements at the end of the specimen are monitored with eddy-current displacement sensor connected to NI9215 module. For cycle counting, the signal from eddy current sensor is transformed to pulses and connected to counter input of NI9401 module. Temperature is monitored with a thermocouple connected to NI 9211 module. The hot end of the thermocouple is glued to the center of the specimen.

Cooling system

A circular cooling system was designed for preventing specimen heating during operation. Drilling oil as a cooling agent is used.

Abstract: In this article questions about fatigue endurance limit of Az91 Mg-alloy was discussed. Very high cycle fatigue testing at 20kHz (push-pull mode) was done. An ultrasonic testing system developed in Technical University of Varna was used. Questions about fracture micromechanics and crack initiations were also discussed.

Keywords: VHCF, MG-ALLOY, FATIGUE ENDURANCE LIMIT;
3. Experimental Procedure

Specimen Preparation

Cast Mg-alloy AZ91 (Mg-9Al-1Zn) with chemical composition given in table 1 is used for this study. Specimens were cut from ingot and machined. "Hourglass" specimens with appropriate shape and dimensions were prepared, fig. 2. Diameters of cylindrical part and the throat, as well as length of reduced part were technologically chosen. Analytical solution given in [15] of the longitudinal wave equation for obtaining the resonance length and radius of reduced part is used. Dimensions from analytical solution were verified by FEM frequency modal analysis [19].

It has to be mentioned that for proper design of the specimen exact values for Dynamic Young’s Modulus and density have to be obtained. Since experimentally measured density (Archimedes’ method) is ρ=1812kg/m³, practically identical with values given in the booklets, critical parameter is Young’s modulus which has to be determined experimentally for the investigated pieces of material. In this study cylindrical samples (φ10x100) for dynamic Young’s modulus measurement was cut from ingot and machined. Impulse-resonance method according to ASTM E1876 [20], was applied. Mean value for dynamic Young’s modulus, obtained by exiting fundamental longitudinal mode of the samples, is E=42.45GPa.

Fatigue Calibration

Calibration was done with cylindrical test specimen with λ/2 resonance length (L=121mm). Since applied voltage is linearly proportional to displacement amplitude at the end and stress in the middle of the specimen, they are simultaneously measured using test equipment shown on fig. 3. Stress is measured with strain gauge (1) mounted in the middle of the specimen and displacement amplitude by gauge indicator (2) with 0.001mm precision.

Fatigue testing

For fatigue testing 10⁸ cycles are chosen as an endurance limit. Specimens were constantly cooled in order to keep temperature around 25°C. Stress amplitude is controlled by changing voltage to the piezoceramic transducer.

4. Results and Discussion

Ultimate tensile strength Rm=167MPa and elongation A=2.9%, were determined from static tensile test. These values are in the range of standard for such alloys [21].

Microstructure consists of α-Mg, eutectic α+γ and discontinuous precipitations of γ-phase (Mg17Al12), fig. 4.

Fatigue life result, in the range 10⁵-10⁸ cycles are presented in the form of S-N diagram, fig. 4. Fatigue limit at 10⁸ cycles is in the range 44-55MPa. Using staircase method, mean fatigue strength is estimated to σf⁰=49.8MPa, standard deviation to Sd=5.5MPa, so lower fatigue strength estimated on 90% reliability is σf⁰=40.4MPa. Such values for fatigue strength are similar to those obtained from researches in [9, 10, 12, 14].

In the fatigue failure zone (fig.5) dispersion of the results is high, so adequate fatigue equation cannot be obtained. One of the possible reasons for this is the presence of cast defects in tested samples (voids, pores, structural inhomogeneity). Presence of such defects, their nature, size, orientation and distribution, are detrimental to fatigue endurance of specimens. Experimental values can be divided to two regions. The most likely reasons for fatigue crack initiation and development in terms of specimens failed in the first region (1-10⁵-10⁶ cycles), is a presence of internal voids. However region “I” may be divided into two subregions: a broken at relatively high stress specimens (A), and broken at lower load values specimens (B).

In specimens of group (A) sites of the fatigue cracks initiation are predominantly close to the surface voids. The possibility of this is determined by the high values of the applied stress amplitude in the order of 70-90 MPa. This is proved from the broken surface shown on fig. 6. Crack origins are shown with arrows. Relatively low cycle crack development in this case leads to formation of rough fracture surface. Static fracture zone is missing. For specimens of group (B) main reason for fatigue fracture is presence of γ-Mg17Al12 precipitations.
of large voids or group of voids, which cause high stress concentration leading to fast fracture at relatively low amplitude stresses.

As for the experimental results of the second area ("II"-10^7-10^8, fig.5.), the most likely reason of fatigue fracture is the presence of structural heterogeneity. Microstructure of the alloy from which the samples are made, shown on fig 3 is conformation. The presence of clearly visible discontinuous γ-phase precipitations is possible reason for the initiation and development of fatigue crack in high-cycle fatigue region.

Fractured surface of specimen cycled with stress amplitude σa=55MPa and failed at N=5.42x10^7 cycles is shown on fig.7. The fatigue crack propagation area (zone II) and the static fracture (zone I) are clearly visible. The crack origin is at the surface. Probably fatigue cracks developed from microcracks initiated at the phase border between γ-phase (Mg17Al12) precipitations and the main α-Mg matrix. Heat treatment to dissolve these precipitations can improve strength of the alloy [10].

5. Conclusions

Based on the ultrasonic fatigue test at frequency 20KHz in “push-pull” mode with symmetrical cycle loading (R=-1), of the fatigue life of the studied magnesium alloy AZ91 in the range 10^5-10^7 cycles, following main conclusion can be mentioned:

- the mechanism of fatigue damage and the nature of fatigue fracture are strictly dependent on the structural condition of the alloy (microstructure, presence of cast defects);
- if there is casting defects as voids or internal pores, they act as a crack initiation sites and fatigue life is up to 10^6 cycles. Depending on size and distribution of voids specimens can fail at high or low amplitude stresses;
- if there is no large voids fatigue life exceeds 10^7 cycles at amplitude stress less than 80MPa. Fatigue fracture origins are on the surface, probably initiated at the phase border between γ-phase (Mg17Al12) precipitations and the main α-Mg matrix. The fatigue crack propagation area and the static fracture are clearly visible on fracture surface;
- on a base of 10^8 cycles mean fatigue strength of the investigated alloy is σf50=49.8MPa

Acknowledgements

Ultrasonic fatigue machine used for the experiments was developed with the financial support of Bulgarian “Science Research” fund under the project DMU03/98.

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