Fatigue resistance of magnesium alloy AZ 91D

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Received 3 May 2006, received in revised form 24 June 2009, accepted 17 September 2009

Abstract

The presented paper brings the results of metallographic and fractographic analysis of fracture surfaces, fatigue crack propagation and fatigue life measured at the high-frequency cyclic loading of Mg-alloy AZ 91D.

Experimentally measured values of the fatigue resistance of the alloy AZ 91D have been influenced, first of all, by the presence of cast defects. The occurrence of these defects, their character, size, orientation, amount, and location on the surface and in the subsurface layers influenced, in a negative way, the fatigue resistance of the studied alloy.

The fatigue behaviour and character of the fatigue fracture of the alloy AZ 91D are highly dependent on structural factors and on the level of technical perfection of their production. The character of the fracture surface morphology depends on the size of the stress amplitude σ_{a}.

Decreasing of expenses as well as increasing of efficiency of whole process of mechanical design and providing of operability during the overall lifetime of parts and machineries allow us to make progress in the field of the utilization of the computational technologies and the application of numerical methods for the solution of huge amount of mechanical engineering praxis problems. Nowadays we have several commercial programs at our disposal, which allow us to solve the crack propagation. Many authors have dealt with influence of the crack growth on the functionality of the particular parts from global point of view.

Key words: magnesium alloy, high-frequency cyclic loading, fatigue tests, numerical methods

1. Introduction

During real operation, the structures are strained by repeated load, which results in fatigue fracture. Therefore, increasing attention is paid to the laws, which govern the fatigue process. If the structure material is exposed to repeated cyclic loading, it is necessary to determine fatigue characteristics as completely as possible. It follows that concrete values have to be determined experimentally: coefficient of fatigue ductility $\varepsilon_{\mathrm{f}}'$, exponents of lifetime curves c, b, coefficient of fatigue resistance σ_{f}', fatigue limit σ_{C}, or timing fatigue limit σ_{CN}, basic threshold amplitude value of stress intensity coefficient K_{ath}, material characteristics A, m, fatigue fracture toughness K_{fc} [1–4]. Experimental defining of the above fatigue characteristics is usually realized by means of general frequencies within the area from $f \approx 10\,\mathrm{Hz}$ to $f \approx 200\,\mathrm{Hz}$, which, in term of time and cost, is very demanding.

One of possible solutions is applying experimental methods of high frequency cyclic loading ($f \approx 20\,\mathrm{kHz}$) for the purpose of defining fatigue properties in structural materials. These experimental methods are efficient as far as time and cost concern [5–8].

Nowadays, magnesium and its alloys are very interesting materials for practice. Its advantage is due to the lowest specific weight among all metals used for structural purposes, declining availability and rising prices of raw materials, as well as subsiding supply of metals on a world scale. Mechanical properties of pure magnesium are not favourable. It has low strength and ductility due to its crystalline structure. However, by alloying we can obtain important structural materials. Suitable alloying partially eliminates

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Table 1. Chemical composition (mass %) of Mg-alloy AZ 91D

	Al	Zn	Mn	Si	Cu	Fe	Be	Pb
AZ 91D	7.98	0.63	0.22	0.045	0.007	0.013	0.0003	0.057

Table 2. Mechanical characteristics of Mg-alloy AZ 91D

	R_m (MPa)	A_5 (%)	Z (%)	$\mathrm{HB}_{2.5/62.5/30}$
AZ 91D	223	8.0	0.5	64.2

occurrence of casting defects, considerably increases strength, toughness, resistance against corrosion, and castability [9].

Outstanding features of commercially used magnesium alloys are their low specific weight, good castability, machinability, and weldability in protective atmosphere. Drawbacks which restrict their wider employment are caused by low modulus of elasticity, limited resistance against creeping at higher temperatures, high shrinkage during hardening, and, first of all, low resistance against corrosion arising from their high chemical reactivity [6, 7].

Low specific weight and ability to absorb vibrations make them suitable for applications in automobile, aviation and rocket industries as well as in telecommunication and instrumentation. The most widely used Mg alloys in industry are those based on Mg-Al-Zn-(Si) and Mg-Al-Mn [9–11].

The submitted paper introduces results of Mg alloy AZ 91D fatigue lifetime ($\sigma_\mathrm{a} = f(N)$, growth trajectory of fatigue crack and fractographic analysis) obtained under high-frequency cyclic loading within the region of high number of cycles from $N = 6 \times 10^5$ cycles to $N = 1 \times 10^9$ cycles.

Linear and non-linear fracture mechanics analysis can be performed with ADINA system including computation of conservation criteria (J-integral and energy release rate) in 2D and 3D finite element models. The fracture mechanics, however, allows performing an analysis with only one crack. The crack line or surface can be located on the boundary or inside the finite element model.

2. Experimental material

Experiments were carried out with AZ 91D magnesium alloy, which is mainly used in the automobile industry. Chemical composition and mechanical characteristics are shown in Tables 1 and 2. Fatigue tests were realized on KAUP-ZU Zilina testing equipment, at high-frequency cyclic loading of the push-pull type

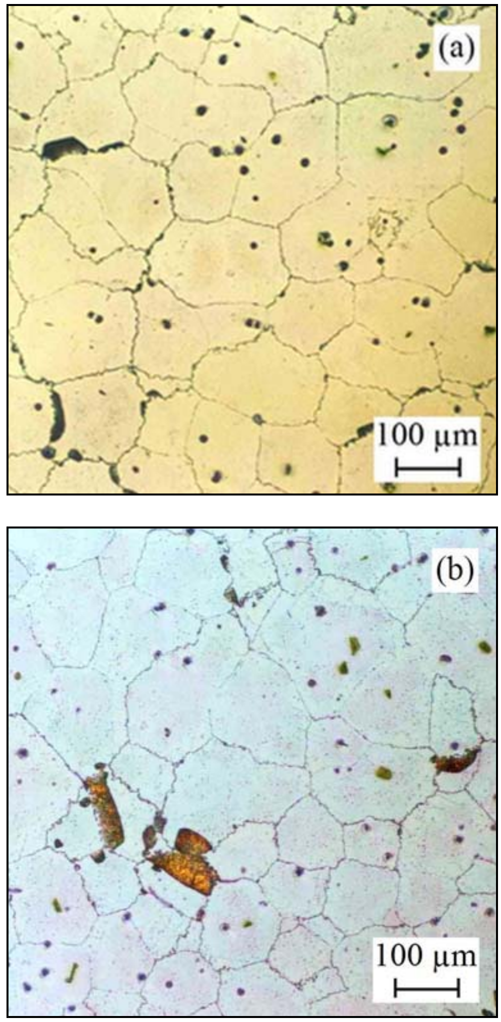

Fig. 1. Microstructure of Mg-alloys AZ 91D, magnified 100×, etched by 5 % molybdenum acid: (a) plate centre – phase δ grain size 4, discontinuous precipitate of phase γ (electron compound $Al_{12}Mg_{17}$); (b) plate edge – phase δ grain size 5, discontinuous precipitate of phase γ (electron compound $Al_{12}Mg_{17}$).

($f \approx 20$ kHz, $T = 20 \pm 10$ °C, $R = -1$, cooling in NaOH solution).

Magnesium alloy was delivered after being cast into sand moulds in the form of half-finished products, i.e. plates with dimensions $21 \times 100 \times 200\ \mathrm{mm}^3$. The alloy was thermally processed in T4 mode – dissolving annealing. Due to non-uniform hardening in the course of experimental material cooling, samples were taken from the plate edge as well as the plate middle.

Microstructure of magnesium alloy AZ 91D samples after thermal processing (Fig. 1) is created by uniform polyedric grains of phase δ. The grain size (assessed according to STN 42 0462) is not the same in the whole cast body. Bigger grain has been observed in samples taken from the plate middle (grain size 4) (Fig. 1a) when compared to the samples taken from

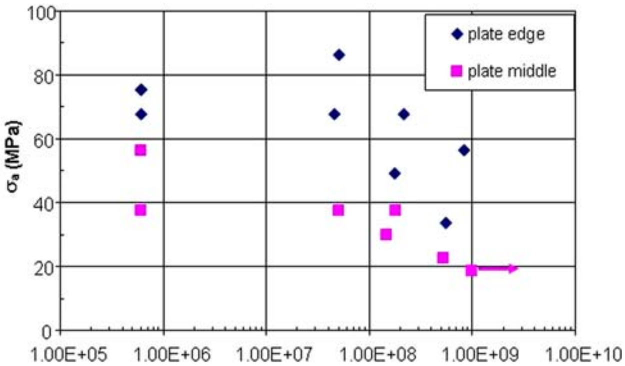

Fig. 2. Dependence of $\sigma_a = f(N)$ for Mg-alloy AZ 91D (conditions: cyclic loading of the push-pull type, $f \approx 20$ kHz, $T = 20 \pm 10$ °C, $R = -1$, cooling in NaOH solution).

the plate edge (grain size 5) (Fig. 1b). At some places, within the grain boundaries there has been found the presence of small amount of discontinual precipitate consisting of fine lamellas of phase γ (electron compound $Al_{12}Mg_{17}$) in the matrix of δ phase.

3. Results and discussion

On the tested magnesium alloy AZ 91D, the dependence $\sigma_a = f(N)$ in the region from $N \approx 6 \times 10^5$ to $N \approx 1 \times 10^9$ cycles to fracture has been studied. Experimentally measured values of the fatigue resistance (Fig. 2) show relatively high dispersion. This dispersion of the measured values has been caused, first of all, by the presence of cast defects (micropipes, structural heterogeneities). The occurrence of these defects, their character, size, orientation, amount and location on the surface and in subsurface layers influenced in a negative way and to a various degree of strength the fatigue resistance of the studied alloy. Experimental results show an obvious difference in the values measured on specimens taken from the plate middle (A) and the plate edge (B). Different size of grains (Fig. 1a,b), caused by different speed of hardening and cooling at the plate middles and at the plate edges in the course of casting, plays here a considerable role.

The fractographic analysis of fracture surfaces of specimens disturbed by fatigue has shown that the fatigue cracks, almost in all cases, have been initiated from the surface of the specimens (Fig. 3a). In most cases, an initiation place was a cast defect reaching to the surface of the specimens (Fig. 3b). The cast defects were mostly microscopically small, nevertheless, their occurrence was very frequent and sometimes they created rather a wide network. Parts of fracture surfaces that showed signs of fatigue failure had a transcrystallic character (Fig. 4) for the most part. The failure character of specimens taken from the plate middle and plate edge has not disclosed any substantial differences from the fractographic point of view. The fracture surfaces generally have had a mixed character of failure. In addition to facets having character of transcrystallic fatigue failure, on the fracture surfaces there also appeared intercrystallic facets. Clearly visible fatigue grooving could be observed at the studied fracture surfaces very seldom only.

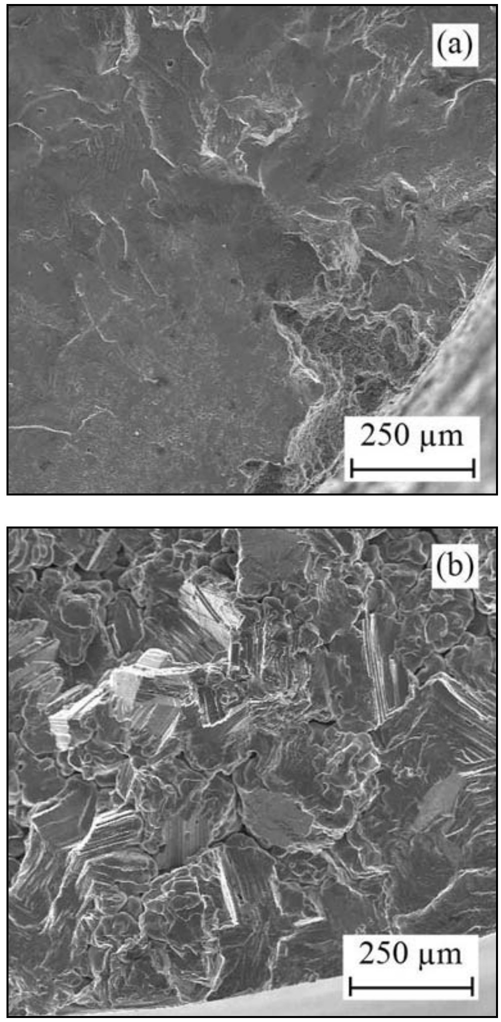

Fig. 3. Initiation of fatigue crack (mostly from cast defects on the surface of the specimens), Mg-alloy AZ 91D: (a) initiation from the surface of the specimens, (b) a cast defect reaching to the surface of the specimens.

The character of fracture surface morphology was to a considerable degree dependent on stress amplitude σ_a. Morphology of fatigue fracture areas of specimens disturbed at lower values of σ_a appeared to be less relief. At higher σ_a values the fatigue fracture areas were more relief. In general, the fatigue areas had a mixed character of failure and in addition to facets having character of transcrystalline fatigue fail-

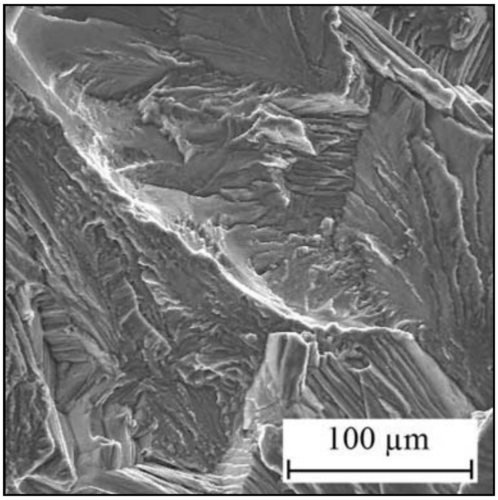

Fig. 4. Transcrystalline fatigue failure, Mg-alloy AZ 91D.

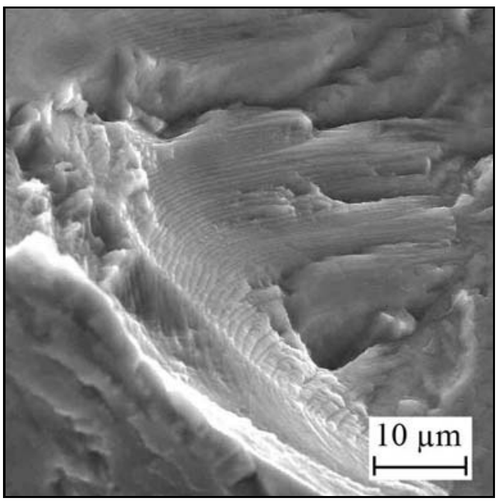

Fig. 5. Detail of fatigue grooving, Mg-alloy AZ 91D.

ure, intercrystalline facets occurred at fracture areas, too. Fatigue grooving (Fig. 5) at fracture areas could be observed very seldom only. Disturbance character of tested samples taken from the edge and middle of plates did not show any substantial differences from the fractographic point of view.

The fatigue cracks, which were observed in AZ 91D magnesium alloy, propagated in a transcrystalline way (Fig. 6). At higher values of stress intensity factor the trajectory of fatigue crack was less bifurcated and propagation of fatigue cracks was accompanied by an intensive slip (Fig. 6). With gradually decreasing value of stress intensity factor the trajectory of fatigue cracks became more bifurcated and the propagating crack started to copy their boundaries in their proximity. At low values of stress intensity factor, this effect manifested relatively often and the traject-

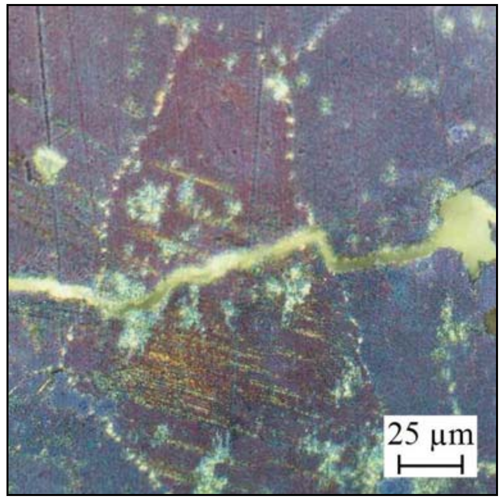

Fig. 6. Transcrystalline fatigue crack propagation with slip bands, Mg-alloy AZ 91D.

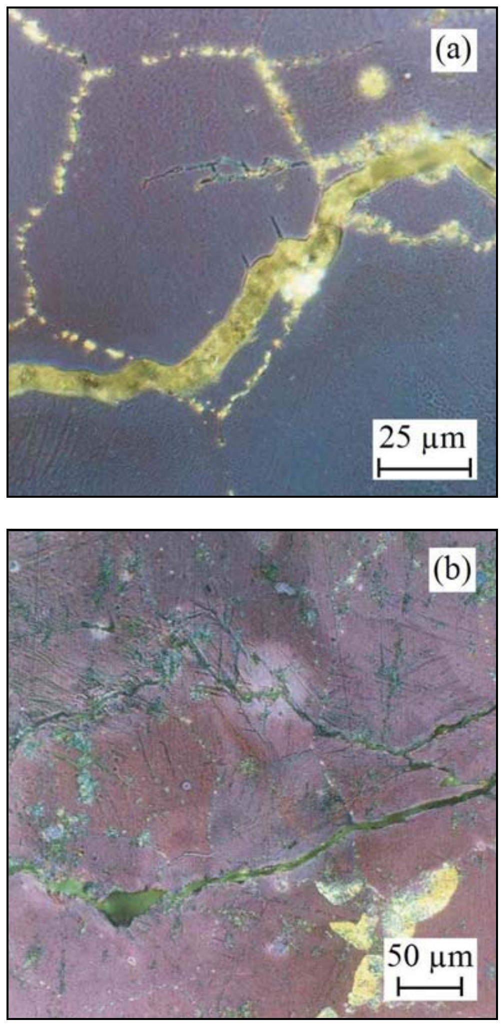

Fig. 7. Fatigue crack propagation trajectory, Mg-alloy AZ 91D: (a) crack copied the grain boundaries at their close vicinity, (b) branching of cracks.

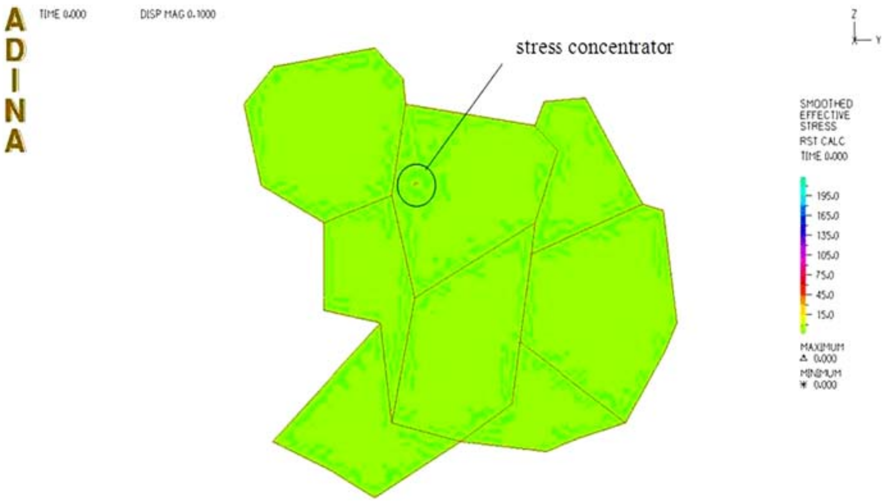

Fig. 8. Model of microstructure with primary stress concentrator before applied load.

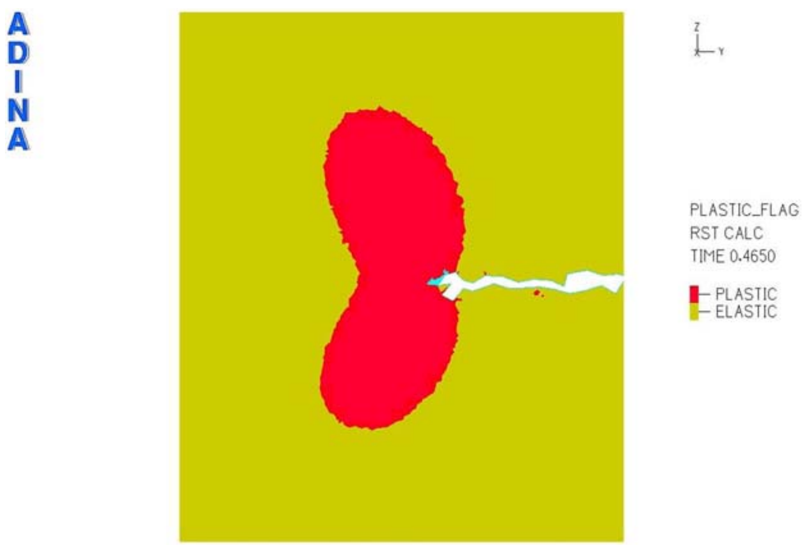

Fig. 9. Plastic zone at the crack tip.

ory of fatigue crack copied here and there grain boundaries at their close proximity (Fig. 7a). At very low values of stress intensity factor within near-threshold region, there occurred branching of cracks as well as an extensive network of secondary cracks (Fig. 7b).

The microstructure of the material represented by tightly packed grains was modelled by using the finite-element software ADINA. The geometry of each grain was modelled by Pro/Engineer software and was exported as a plain surface in IGES file to ADINA, where a 2D dynamic analysis was performed. The analysis was performed by using large deformations and large displacements incorporated into the mathematical model.

Each grain was considered as a stand-alone body and contact conditions between each pair of grains were implemented. In the microstructure model a stress concentrator was made (Fig. 8). Issue of damage propagation of materials in the microstructure is considerably demanding for the exact model.

On the boundaries was applied a cyclic load with amplitude 30 MPa and with frequency 25 Hz in a pull-push fashion for a period of 4 seconds, which means that 100 cycles were applied altogether.

The propagation of material damage was governed similarly to crack propagation, where a plastic zone (Fig. 9) is created in the vicinity of the crack tip in which a plastic strain is accumulated due to cyclic loading. The deformation process at the crack tip depends significantly on the mechanical properties of the material and on the environment in which the loading occurs. The crack propagation (Fig. 10) occurs in the direction of maximum shear stress and its direction gradually changes into direction perpendicular to

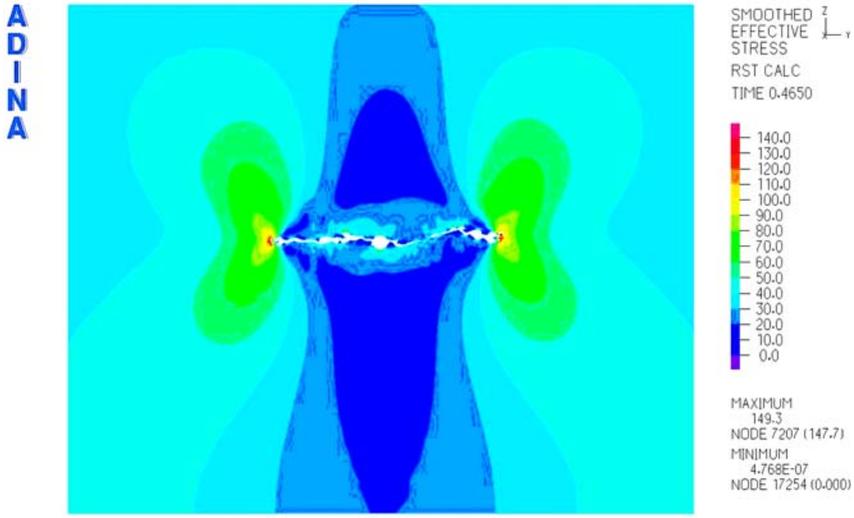

Fig. 10. Fatigue crack propagation and redistribution of stress.

the direction of applied load. The orientation of main stresses inside each grain is changing depending on the orientation of the grains, their shape and the spread of the damage.

4. Conclusion

Experimental assessment of the fatigue resistance of the studied AZ 91D magnesium alloy in the region of high number of loading cycles ($N \approx 6 \times 10^5 \div 1 \times 10^9$ cycles), carried out at high-frequency cyclic loading ($f \approx 20$ kHz, $T = 20 \pm 10$ ℃, $R = -1$) showed that:

– appearance of casting defects, their character, size, orientation, amount, and localization at the surface and subsurface layers with various intensity, influence fatigue resistance of the studied Mg-alloy in a negative way;

– studying trajectory of fatigue cracks propagation in the observed AZ 91D Mg-alloy showed ruggedness of growth (branching, linking, secondary cracks, stages...) as a consequence of interaction of crack front with micro-structural factors (casting defects, grain boundaries, intermetallic particles and the like);

– fatigue behaviour and character of fatigue fracture of AZ 91D alloy are considerably dependent on structural factors and level of technical perfection of their production;

– the obtained knowledge showed principled possibility of efficient verifying fatigue characteristics within a wide range of number of loading cycles (from $N = 1 \times 10^5$ to $N = 1 \times 10^9$ cycles) at the high-frequency cyclic loading ($f \approx 20$ kHz);

– the values of stress amplitude σ_a at the number of cycles $N = 1 \times 10^9$ cycles have been $\sigma_a = 55$ MPa (plate edge) and $\sigma_a = 18$ MPa (plate middle);

– the FEM software ADINA enables us to observe the growth of fatigue damage and crack propagation in a model as well as to observe the distribution of stress fields.

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