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# THE STUDY OF LOW CYCLIC BEHAVIOUR OF AZ61 MAGNESIUM ALLOY

# STUDIE NÍZKOCYKLOVÉHO CHOVÁNÍ HOŘČÍKOVÉ SLITINY AZ61

**Abstract**

This paper deals with the investigation of fatigue behaviour of AZ61 magnesium alloy made by squeeze casting technique. Fatigue tests were conducted in the regime of controlled total plastic strain on the smooth cylindrical specimens. The standard tensile curve was compared with cyclic stress-strain curve. The comparison indicates that studied material exhibited cyclic hardening at whole lifetime. The measured data were subsequently used for assessing the Manson-Coffin and Wöhler-Basquin curves and for fitting with suitable regression functions for determination of the fatigue parameters.

**Abstrakt**

Práce je zaměřena na určení únavového chování v nízkocyklové oblasti hořčíkové slitiny AZ61 odlité metodou squeeze casting (SC). Testy probíhaly v módu řízení amplitudy celkové deformace na hladkých válcových zkušebních tělesech. Porovnáním tahové křivky s cyklickou deformační bylo zjištěno, že zkoumaný materiál cyklicky zpevňuje v celém průběhu. Na základě naměřených experimentálních dat a přímé analýzy zaznamenaných hysterezních smyček byly vyneseny a regresními funkcemi proloženy cyklická deformační křivka, Masonova-Coffinova a odvozená Wöhlerova-Basquinova křivka. Srovnáním takto získaných regresních parametrů s odpovídajícími rovnicemi byly stanoveny únavové parametry studované slitiny.

## 1 INTRODUCTION

Magnesium alloys are used in the automotive, aerospace, and electronics because of their light weight and high strength-to-weight ratio. The use of magnesium alloys in structural applications is the most active area [1]. A reduction in the weight of vehicles would not only help in minimizing the fuel consumption and emission levels, but would to a great extent enable the automobile and aviation industries to improve passenger and transportation capacities [2]. Disadvantages of magnesium alloys are the low modulus of elasticity and high magnesium reactivity causing low corrosion resistance, which poses high claims on the magnesium alloys preparation. To get castings with high quality surface, fine cast structure and minimum porosity means to use the squeeze casting method. It is two-step alternative of pressure casting [3, 4]. This technique was used in the present study to better assess the fatigue behaviour of the experimental material.

## 2 EXPERIMENTAL MATERIAL

The testing specimens were made from raw casting AZ61 magnesium alloy made by squeeze casting technique shaped as a cylinder with dimensions 204 mm in diameter and height 36 mm.

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The experimental material was used in basic condition (i.e. without heat treatment). The dimensions of testing cylindrical proportional specimens were 6 mm in diameter and length 30 mm for determination basic mechanical properties. For fatigue tests were used cylindrical specimens with treated heads, 6 mm in diameter and length 14 mm.

The chemical composition of experimental material measured by glow discharge optical emission spectroscopy (GDOES) using Spectrumat GDS-750 device is given in Table 1. This data represents the average of three measured. Content of magnesium is the rest to 100 wt. %.

**Tab. 1** Chemical composition of AZ61 magnesium alloy

| | Al | Zn | Cu | Mn | Si | Fe | Ni | Be |
|---|---|---|---|---|---|---|---|---|
| [wt. %] | 6.19 | 1.87 | 0.00 | 0.39 | 0.013 | 0.004 | 0.00 | 0.001 |

## 3 EXPERIMENTAL PROCEDURE

The basic mechanical properties were determination by using the universal PC controlled TiraTest 2003 testing machine.

Fatigue tests were conducted on a servohydraulic PC controlled Instron 8801 machine in regime of controlled total strain. Tests were performed with total strain amplitudes from 0.25 to 1.2 %. All fatigue test bars were loaded at constant speed of strain 0.01 $s^{-1}$ with symmetrical triangle push-pull loading cycle (parameter of loading cycle asymmetry was $R_\varepsilon = -1$). Strain was measured with an axial extensometer with a base length of 12.5 mm.

During tests were continuously recorded hysteresis loops in digital form and extreme values of stress and strain. The responses for the loading levels of stress and plastic strain were evaluated from analysis of these loops. Fig. 1 illustrates the evolution of stress amplitude with cycles for strain amplitude $\varepsilon_a$ = 0.6 %. Number of cycles to fracture $N_f$ was determined by the drop of parameters criterion $\sigma_m/\sigma_a$ to the value -0.05.

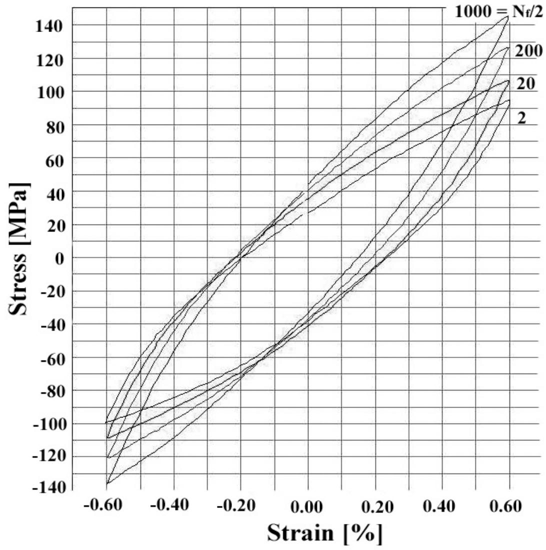


**Fig. 1** Hysteresis curves of representing cycles, amplitude $\varepsilon_a$ = 0.6 %.

## 4 RESULTS

The microstructure of AZ61 magnesium alloy is in two different magnifications recorded in Fig. 2. The structure was composed of solid solution δ (i.e. Al in Mg), the intermediate phase γ ($Mg_{17}Al_{12}$) which was precipitated on grain boundaries and furthermore were observed polyedric inclusions based on Mn and Al.

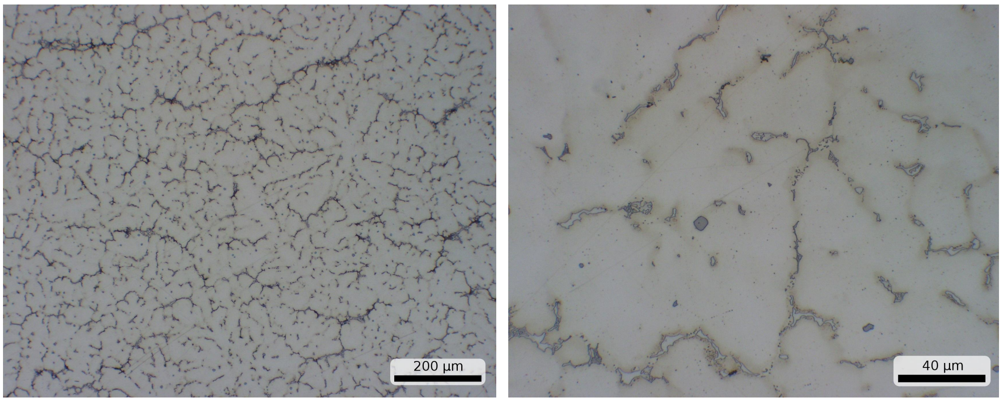


**Fig. 2** Microstructure of AZ61 magnesium alloy, etch picric acid solution, LM

The average of three measurements of basic stress and strain characteristics obtained by static tensile tests and hardness tests are given in Table 2.

**Tab. 2** Mechanical properties of experimental material

| E [GPa] | $R_m$ [MPa] | $R_{P0.2}$ [MPa] | A [%] | Z [%] | HBW 5/125 |
|---|---|---|---|---|---|
| 41 | 175 | 79 | 5 | 5.3 | 57 |

The cyclic stress-strain curve, i.e. stress amplitude dependence of plastic strain deformation, of the AZ61 alloy in log-log coordinates fitted with regression function is plotted in Fig. 3a). The cyclic strength coefficient *K´* and cyclic strain hardening exponent *n´* were obtained by the comparison equation of the regression function with equation (1). With using these coefficients and equation (2) were determined cyclic yield strength $R_{p0.2}$*’* [5]. The determined data are given in Table 3.

The comparison of static tensile curve with cyclic stress-strain curve (see Fig. 3b) confirms and refines the results obtained in Fig. 3a. The cyclic yield strength $R_{p0.2}$*”* is given in this figure. The measured data constituting the cyclic stress-strain curve were fitted with modified Ramberg-Osgood function (3) [6]. Its parameters, i.e. stress amplitude *σ*, Young´s modulus *E*, initial stress amplitude $\sigma_0$ and cyclic strain hardening exponent *n* are given in Table 4. The monotonic curve was also fitted with modified Ramberg-Osgood function for determine material parameter (Tab.3).

$$s_a = K^{'} \cdot e_{ap}^{n^{'}} \tag{1}$$

$$R_{p0.2}^{'} = K^{'} \cdot 0.002^{n^{'}} \tag{2}$$

**Tab. 3** The values of regression parameters

| Wöhler-Basquin | | Manson-Coffin | | Cyclic Curve | | |
|---|---|---|---|---|---|---|
| $\sigma^{'}_f$ | b | $\varepsilon^{'}_f$ | c | $K^{'}$ | $n^{'}$ | $R_{p0.2}^{'}$ |
| MPa | - | - | - | MPa | - | MPa |
| 440.35 | -0.1392 | 0.2481 | -0.5989 | 614.78 | 0.2339 | 143.70 |

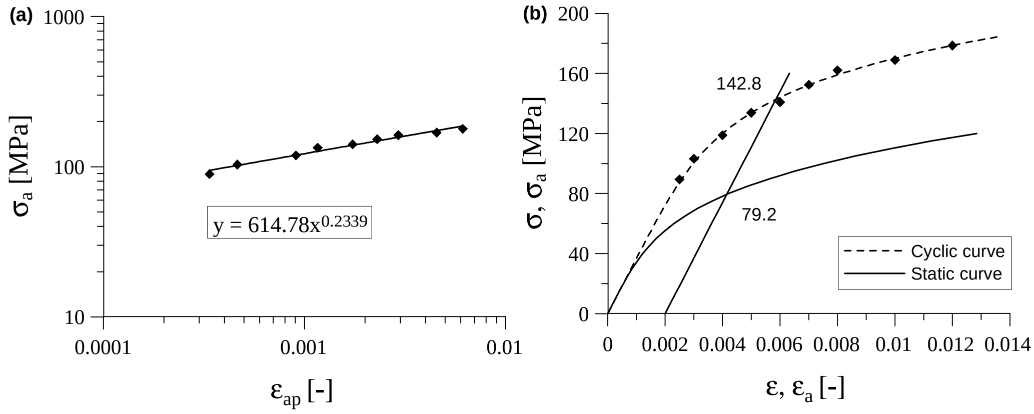


**Fig. 3** (a) Cyclic stress-strain curve, (b) comparison of tensile curve with cyclic stress-strain curve

$$e(s) = \frac{s}{E} + \left(\frac{s}{s_0}\right)^n \tag{3}$$

**Tab. 4** Summary of material parameters

| Ramberg-Osgood Cyclic Curve | | | | Ramberg-Osgood Static Curve | | | |
|---|---|---|---|---|---|---|---|
| E | $\sigma_0$ | n | $R_{p0.2}$“ | E | $\sigma_0$ | n | $R_{p0.2}$ |
| MPa | MPa | - | MPa | MPa | MPa | - | MPa |
| 36790 | 424.49 | 5.7128 | 142.80 | 37235 | 408.49 | 3.7910 | 79.2 |

Curves of cyclic hardening-softening of the studied material as dependence of stress amplitude on number of cycles are shown in Fig. 4a) and as dependence of plastic strain amplitude of number of cycles in Fig. 4b).

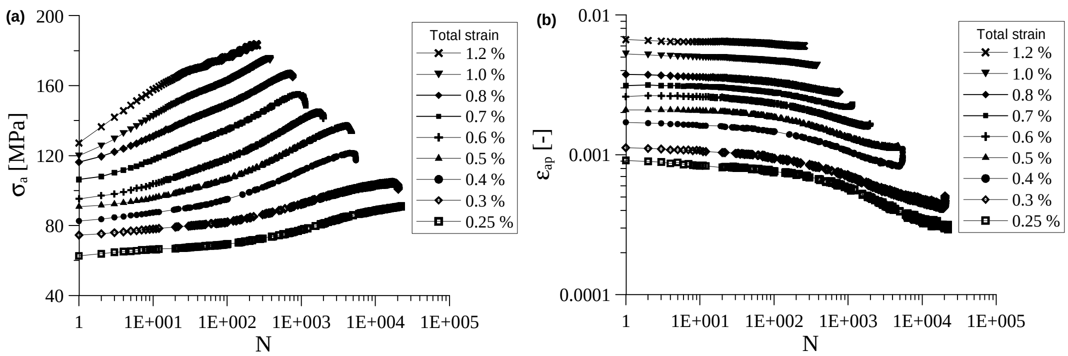


**Fig. 4** Curves of cyclic hardening-softening (a) course of stress amplitude, (b) course of plastic strain amplitude

The Wöhler-Basquin curve plotted by regression analysis is shown in Fig. 5a). This dependence was compared with equation (4) [7] and were determined fatigue parameters, i.e. fatigue strength coefficient $\sigma'_f$ and elastic exponent of lifetime curve $b$ (see Tab. 3).

$$s_a = s'_f \cdot (2N_f)^b \tag{4}$$

The Manson-Coffin curve accordance with equation (5) [7] is plotted in Fig. 5b). Determined low-cycle fatigue parameters, i.e. fatigue ductility coefficient $\varepsilon'_f$ and plastic exponent of lifetime curve $c$ are also given in Table 3.

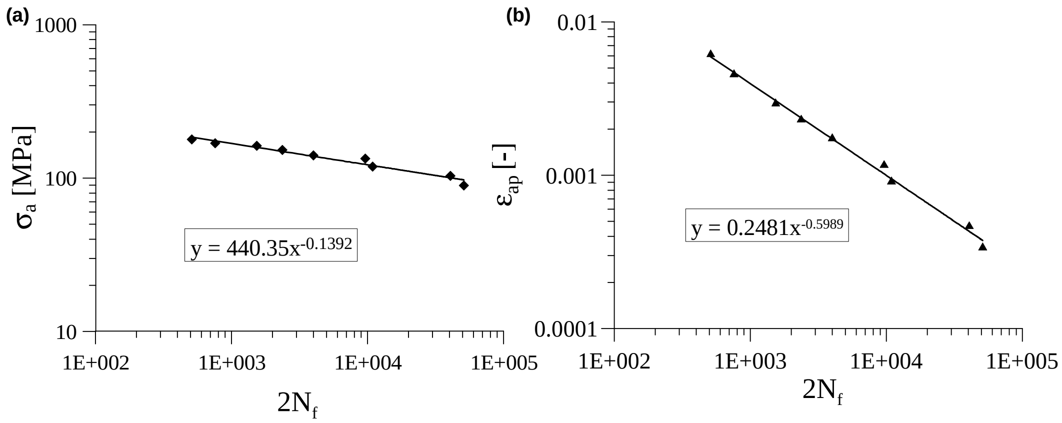


**Fig. 5** (a) Wöhler-Basquin curve and (b) Manson-Coffin curve of AZ61 magnesium alloy

$$e_{ap} = e'_f \cdot (2N_f)^c \qquad (5)$$

The relation between total strain amplitude and the number of cycles to fracture is shown in Fig. 6. With the total strain amplitude $\varepsilon_{at}$ also its two components are shown there, i.e. the plastic strain amplitude $\varepsilon_{ap}$ and the elastic strain amplitude $\varepsilon_{ae}$, which were fitted with suitable power regression functions. The dependence of total strain amplitude on the number of cycles to fracture has been properly fitted as the sum of plastic and elastic strain amplitudes (6).

$$e_{at} = e_{ap} + \frac{s_a}{E} \qquad (6)$$

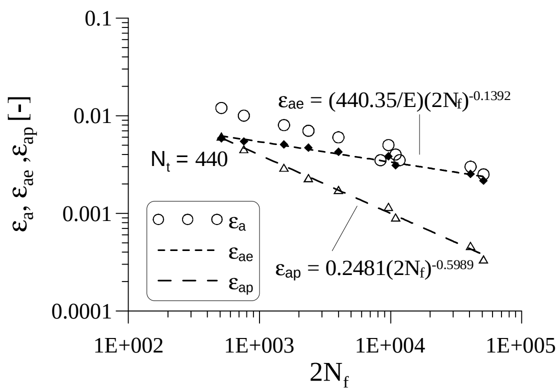


**Fig. 6** Calculation of cycles to failure by the Manson–Coffin rule

## 5 DISCUSSION

The AZ61 magnesium alloy made by squeeze casting technique was investigated in the present study. The microstructure was observation by light microscope and structure was composed of solid solution, intermetallic phases $Mg_{17}Al_{12}$ on grain boundaries and inclusions based on Mn and Al.

The measured mechanical properties (Table 2) were compared with results in the study of authors Chamos et al. [8] and Rusz et al. [9] and it´s clear that these values were below the maximum due to technique of preparation (i.e. casting) and also due to basic state of experimental material (without any heat treatment).

Fig 1 shows a typical change of shape of hysteresis loops during the cyclic loading. The stress responses were approximately symmetrical to given value $\varepsilon_{at}$. From the shape of hysteresis loops it can be assume greater degree of reversible plastic strain. This effect was significant at the higher levels of loading cycle.

Fatigue behaviour of studied material can be predicted in accordance with Manson [10] by the ratio $\boldsymbol{R_m}/\boldsymbol{R_{p0.2}}$. The ratio of the AZ61 alloy was greater than 1.4, it means the material was cyclically hardening. Thus the prediction of cyclically hardening was consistent with the measured data.

Fig. 3b) shows that the stress-strain curve is located above the tensile curve with the identical linear section. Further it´s clear significant increase in cyclic yield strength $\boldsymbol{R_{p0.2}}^{“}$ = 143 MPa versus static yield strength $\boldsymbol{R_{p0.2}}$ = 79 MPa.

Curves of cyclic hardening-softening determined by direct analysis of hysteresis loops are shown in Fig. 4. The material was cyclically hardening throughout the fatigue life. It´s clear (see Fig. 4a) that this effect was especially significant for higher total strain amplitudes and during fatigue life any saturation was observed. For example, for the total strain amplitude $\varepsilon_{at}$ = 1.2 % the stress response was increase by 45%. The amplitude of plastic strain to the contrary during fatigue life was slightly decreasing (see Fig. 4b). This behaviour was the most evident for the lowest amplitude of total strain (closing the hysteresis loop).

The value of stress amplitude $\sigma_a$ = 39.6 MPa was determined by extrapolating the fitted Wöhler-Basquin curve for $10^7$ cycles.

The value of plastic strain amplitude $\varepsilon_{ap}$ = 1.028x$10^{-5}$ was determined by extrapolating the fitted Manson-Coffin curve, this value is accordance with Polak [5]. Contrary, it´s also possible predict lifetime for a given plastic strain amplitude, for example, for plastic strain at the yield strength $\varepsilon_{ap}$ = 0.002 is lifetime 1558 cycles.

## 6 CONCLUSIONS

The microstructure of AZ61 alloy was composed of solid solution δ with phase γ precipitated on the grain boundaries and further polyedric inclusions based on Mn and Al were randomly occurred.

The basic mechanical properties were determined by static tensile test: average tensile strength $\boldsymbol{R_m}$ = 175 MPa and yield strength $\boldsymbol{R_{p0.2}}$ = 79 MPa. It was also determined elongation to fracture $\boldsymbol{A}$ = 5%, reduction of area $\boldsymbol{Z}$ = 5.3% and Young’s modulus $\boldsymbol{E}$ = 41 GPa. Brinell hardness was measured 57 HBW 5/125.

According to the Manson´s rule was the ratio of studied alloy $\boldsymbol{R_m}/\boldsymbol{R_{p0.2}}$ greater than 1.4, it means the material was cyclically hardening.

The progress of cyclic hardening-softening indicate that any saturation was occurred and the AZ61 is cyclically hardening throughout the fatigue life. For the higher total strain amplitude the stress response was increase by 45%.

The materials parameters were obtained by using regression functions: for Manson-Coffin curve were determined $\varepsilon_f^{'}$ = 0.2481 and $\boldsymbol{c}$ = −0.5989 and for Wöhler-Basquin curve $\sigma_f^{'}$ = 440.3 MPa and $\boldsymbol{b}$ = −0.139.

The value of plastic strain amplitude $\varepsilon_{ap}$ = 1.028x$10^{-5}$ was determined by extrapolating the fitted Manson-Coffin curve and by using material parameters for $N_f$ = $10^7$ cycles.

Similar procedure was used for extrapolating the Wöhler-Basquin curve where for $10^7$ cycles the stress amplitude was determined $\sigma_a$ = 39.6 MPa.

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