Transactions of the VŠB – Technical University of Ostrava, Mechanical Series
No. 3, 2009, vol. LV
article No. 1732

Aneta NĚMCOVÁ[*], **Josef ZAPLETAL**[**], **Tomáš PODRÁBSKÝ**[***]

FATIGUE BEHAVIOUR OF AZ91 MAGNESIUM ALLOY

ÚNAVOVÉ VLASTNOSTI HOŘČÍKOVÉ SLITINY AZ91

Abstract

The paper deals with the determination of principal mechanical properties and the investigation of fatigue behaviour of AZ91 magnesium alloy. The experimental material was made by squeeze casting technique and heat treated to obtain T4 state (solution annealing), when hard, brittle $Mg_{17}Al_{12}$ intermetallic phase is dissolved. The basic mechanical properties (Young's modulus, ultimate tensile strength, yield strength, elongation to fracture and reduction of area) were determinated by static tensile test. Furthermore, fatigue parameters were investigated and standard tensile curve was compared with cyclic stress-strain curve. The comparison indicates that studied material exhibited cyclic hardening at whole lifetime. In addition, the S-N curve on the basis of smooth test bars tested under symmetrical push-pull loading at room temperature was evaluated. The measured data were subsequently used for assessing the Manson-Coffin curve and for fitting with suitable regression function for determination of the fatigue parameters. Fatigue limit σ_C of the studied alloy for 10^8 cycles is approaching 50 MPa. Structure of the studied alloy in the basic state and after heat treatment was observed by light and scanning electron microscopy.

Abstrakt

Práce je zaměřena na stanovení základních mechanických charakteristik a zkoumání únavového chování slitiny hořčíku AZ91. Studovaná slitina byla vyrobena metodou squeeze casting a tepelně zpracována na stav T4 (tj. rozpouštěcí žíhání), které způsobuje rozpouštění tvrdé, křehké intermetalické fáze $Mg_{17}Al_{12}$. Byla provedena statická zkouška tahem a stanoveny napěťové a deformační charakteristiky (modul pružnosti, mez pevnosti, mez kluzu, tažnost a kontrakce). Dále bylo provedeno měření únavových parametrů a srovnána jednosměrná tahová křivka s cyklickou deformační křivkou. Z tohoto srovnání vyplynulo, že studovaný materiál cyklicky zpevňuje. Na hladkých zkušebních tělesech při symetrickém namáhání tah-tlak za normální teploty byla naměřena Wöhlerova-Basquinova závislost a odvozená Mansonova-Coffinova křivka zkoumaného materiálu. Experimentálně naměřená data byla proložena vhodnou regresní funkcí a stanoveny únavové parametry. Mez únavy σ_C studované slitiny pro hladká zkušební tělesa určená pro 10^8 cyklů se blíží 50 MPa. Struktura studované slitiny v základním stavu a po tepelném zpracování byla pozorována světelným a rastrovacím elektronovým mikroskopem.

1 INTRODUCTION

Magnesium is a structural material with one of the lowest densities. The magnesium alloys are actually used for production of sport accessory, mobile phones or computers, but more important applications are in automotive and aerospace industry, therefore the determination of their

---

[*] Ing. Aneta Němcová, Institute of Material Science and Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, Brno, Czech Republic, tel: (+420) 541143175, e-mail: ynemco00@stud.fme.vutbr.cz

[**] Ing. Josef Zapletal, Institute of Material Science and Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, Brno, Czech Republic, tel: (+420) 541143466, e-mail: Pepa.Sanguis@centrum.cz

[***] Prof. Ing. Tomáš Podrábský, CSc., Institute of Material Science and Engineering, Faculty of Mechanical Engineering, Brno University of Technology, Technická 2, Brno, Czech Republic, tel: (+420) 541143150, e-mail: podrabsky@fme.vutbr.cz

mechanical and fatigue properties [1-4] is quite crucial. Low density (1700 kg/m^3) and excellent specific strength (strength to density ratio), good castability and machinability [4-6] can be named among advantages. 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 [7]. 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. The AZ91 magnesium alloy is usually further processed by solution annealing [3, 7, 8].

The aim of the work is to obtain basic mechanical parameters of the AZ91 magnesium alloy in the basic state (as delivered) and after T4 heat treatment, i.e. after solution annealing. Next goal consists in evaluation of the S-N curve on the basis of smooth test bars tested under symmetrical push-pull load in force control regime at room temperature. Measured data were subsequently used for assessing the Manson-Coffin curve and for fitting with suitable regression function for determination of the fatigue parameters and the fatigue limit σ_C.

2 DESCRIPTION OF EXPERIMENT

2.1 Material

The AZ91 magnesium alloy produced by squeeze casting method under pressure 50 and 150 MPa was used in the present study. The casting was shaped as a block dimensioned 100 x 100 x 56 mm. Its chemical composition, measured by glow discharge optical emission spectroscopy (GDOES) using Spectrumat GDS750 device is given in Table 1.

Tab. 1 Chemical composition of the magnesium alloy AZ91 (in wt. %).

AZ 91	Al	Zn	Cu	Mn	Si	Fe	Ni	Mg
Standard	8.1-9.7	0.35-1	< 0.35	0.13-0.35	<0.5	<0.005	<0.03	zb.
Measured	8.2	0.72	0.00	0.22	0.00	0.005	0.00	≈90.8

The microstructures of this alloy without and with heat treatment T4 (413°C/16 hours) obtained by scanning electron microscopy are shown in Fig. 1 and 2.

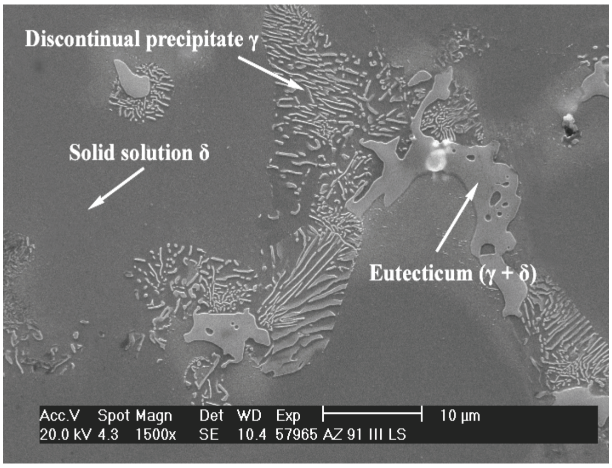

Fig. 1 Microstructure of the AZ91 alloy (squeeze casting), etch picric acid solution, SEM

The local chemical analysis by EDX found out that the structure of alloy without heat treatment is composed of solid solution δ where the intermediate phase γ ($Mg_{17}Al_{12}$) has been precipitated in the shape of discontinuous precipitate with eutectics δ + γ (see Fig. 1). During heat treatment the hard brittle intermetallic phase $Mg_{17}Al_{12}$ was dissolved. It means the microstructure, which is shown in Fig. 2, consists of solid solution δ and inclusions based on Mn.

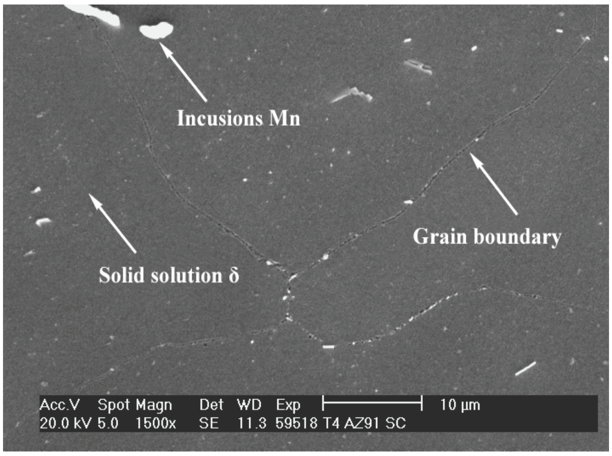

Fig. 2 Microstructure of the AZ91-T4 alloy (squeeze casting), etch picric acid solution, SEM

2.2 Results and discussion

Cylindrical bars of 6 mm in diameter were used for tensile tests. The results of static tensile tests (proof stress $R_{p0.2}$, UTS R_m, elongation to fracture A and reduction of area Z) are given in Table 2 for both states: with and without heat treatment. The results show that solution annealing causes a significant increase in ultimate strength, elongation to fracture and reduction of area accompanied by a slight reduction in yield point, which is due to local coarsening grains.

Tab. 2 Static mechanical properties of the tested AZ91 Mg-alloy together with Young's modulus.

	E [GPa]	$R_{p0.2}$ [MPa]	R_m [MPa]	A [%]	Z [%]
AZ91	43.3	115	175	1.9	2.7
AZ91 – T4	43.1	95	235	9.1	10.4

For fatigue loading the test bars of 6 mm in diameter were used for low-cycle as well as for high-cycle region. Fatigue tests were conducted on a servohydraulic PC controlled Instron 8801 machine. Strain was measured with an axial extensometer with a base length of 12.5 mm. All fatigue test bars were loaded in the regime of controlled force with sinusoidal symmetrical push-pull loading cycle (parameters of loading cycle asymmetry were $R = -1$, i.e. $P = 1$). Fatigue tests were performed at frequency of 3 Hz at room temperature. Fig. 3 illustrates the evolution of plastic strain amplitude with cycles for stress amplitude $\sigma_a = 120$ MPa.

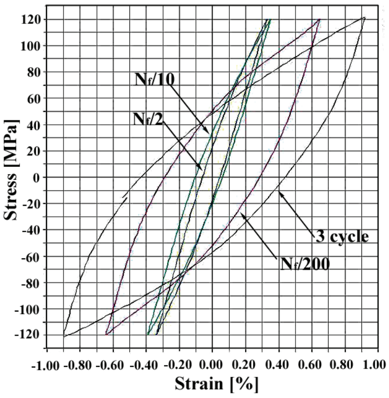

Fig. 3 Hysteresis curves of representing cycles, $\sigma_a = 120$ MPa.

The comparison of standard tensile curve with cyclic stress-strain curve of the AZ91-T4 magnesium alloy is shown in Fig. 4. The solution annealing was performed at 413 °C with the dwell of 16 hours. The parameters of cyclic deformation curves were determined by direct analysis of hysteresis loops measured for individual stress amplitudes of load cycle in half number of cycles to fracture.

Curves of cyclic hardening-softening of the studied material are shown in Fig. 5. The plastic strain amplitude decreases throughout the course of all stress amplitudes, i.e. the material is cyclically hardening. Turnover in the final stage is due to propagation of magistral crack. The effect of cyclic hardening is more significant for lower stress amplitudes of loading cycle.

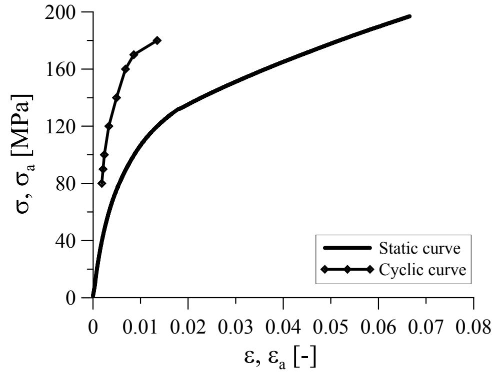

Fig. 4 The comparison of tensile curve with cyclic stress-strain curve of the AZ91-T4 magnesium alloy.

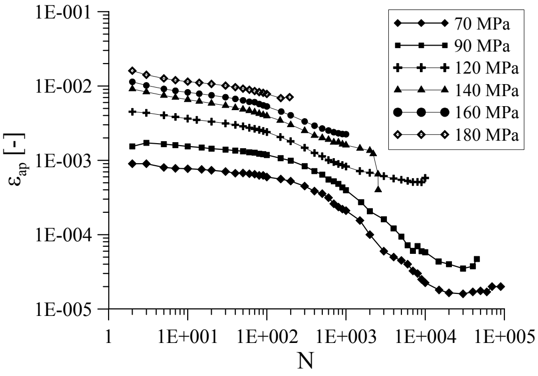

Fig. 5 Curves of cyclic hardening-softening of the AZ91-T4 alloy.

The experimentally obtained dependence of stress amplitude on the number of cycles to fracture in log-log coordinates fitted with suitable regression function is shown in Fig. 6. The Fig. 7 shows the dependence of the plastic strain amplitude for $N_f/2$ on the number of cycles to fracture, i.e. derived Manson-Coffin curve, and the data are fitted with power regression function.

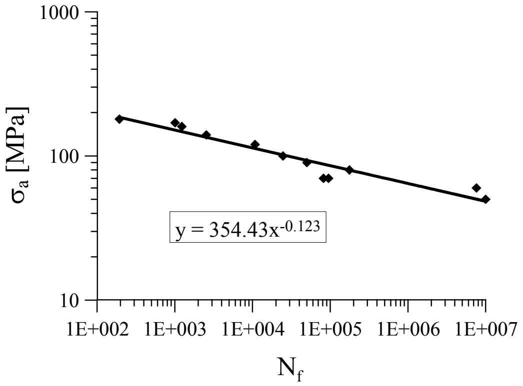

Fig. 6 S-N curve in log-log coordinates of the AZ91-T4 alloy.

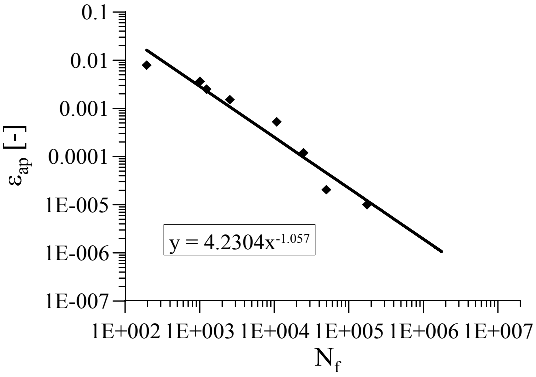

Fig. 7 The Manson-Coffin curve of the AZ91-T4 alloy.

Regression function (see Fig. 6) is formulated as [9]:

$$\sigma_a = \sigma'_f \cdot (2N_f)^b \tag{1}$$

where σ_a – stress amplitude, σ'_f – parameter of fatigue strength, N_f – number of cycles to fracture, b – elastic exponent of lifetime curve.

The dependence in Fig. 7 is also fitted with power regression function [9]:

$$\varepsilon_{ap} = \varepsilon'_f \cdot (2N_f)^c \tag{2}$$

where ε_{ap} – plastic strain amplitude, ε'_f –parameter of fatigue elongation, N_f – number of cycles to fracture, c – plastic exponent of lifetime curve.

The low-cycle fatigue parameters are given in Table 3.

Tab. 3 Parameters of regression functions (1) and (2) of the AZ91-T4 alloy.

σ'_f	b	ε'_f	c
354.43	–0.123	4.2304	−1.057

Fig. 8 shows the dependence of stress amplitude on the number of cycles to fracture (S-N curve) in a more frequent semi-log coordinates. The frequency of loading for the stress amplitude from 70 to 50 MPa was 20 Hz. For stress amplitude 70 MPa slight discontinuity is apparent, which is probably caused due to the increase of the frequency of loading.

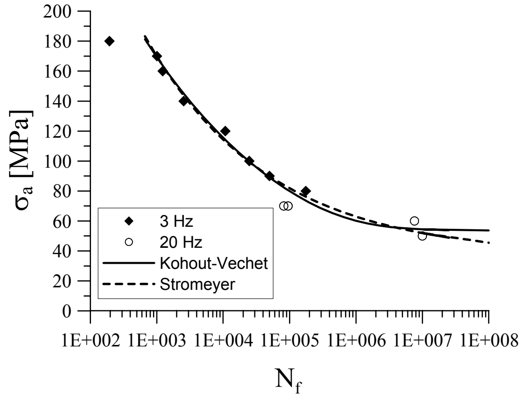

Fig. 8 The comparison of S-N curves using the Stromeyer and the K+V functions.

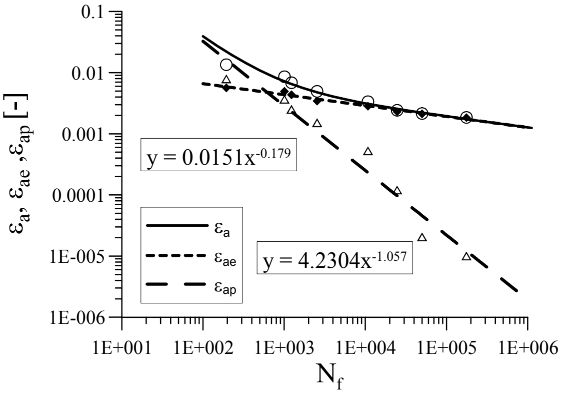

Fig. 9 Calculation of cycles to failure by the Manson–Coffin rule.

Experimentally measured data (see Fig. 8) were fitted with two regression functions [10]:

the Kohout & Věchet function (K+V):

$$\sigma(N) = \sigma_\infty \left(\frac{N}{N+C} \right)^b \tag{3}$$

and the Stromeyer function:

$$\sigma(N) = aN^b + \sigma_\infty \tag{4}$$

where a, b, C a σ_∞ – regression parameters, N – cycles to fracture, σ – stress [MPa].

The values of regression parameters of both the functions together with the sums S of squares of deviations are presented in Table 4, together with fatigue limit values σ_C for 10^8 cycles.

Tab. 4 The values of regression parameters.

Function	a [MPa]	b [-]	C [-]	σ_∞ [MPa]	σ_C [MPa]	S [MPa^2]
K + V (3)	–	–0.1664	1008631	53.6	53.7	562.1
Stromeyer (4)	673.7	–0.2345	–	36.5	45.5	650.0

The relation between total strain amplitude and the number of cycles to fracture is shown in Fig. 9. With the total strain amplitude also its two components are shown there, i.e. the plastic strain amplitude and the elastic strain amplitude, 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:

$$\frac{\Delta\varepsilon_a}{2} = \frac{\Delta\varepsilon_{ae}}{2} + \frac{\Delta\varepsilon_{ap}}{2} \tag{5}$$

3 CONCLUSIONS

1. AZ91 magnesium alloy has been heat treated to the final T4 condition (i.e. solution annealing) for 16 hours at 413 °C. Using metallographic analysis it was investigated that solution annealing leads to dissolution of the $Mg_{17}Al_{12}$ intermetallic phase.
2. The influence of solution annealing is evident from the results of static tensile tests. Comparing the resulting values of tensile tests of materials with and without heat treatment it was found out that after solution annealing ultimate strength R_m and deformation characteristics, i.e. elongation to fracture A and reduction of area Z increase.
3. Analysis of the shape of hysteresis loops and comparison tensile curve with cyclic stress-strain curve of the AZ91-T4 magnesium alloy showed that the cyclic stress-strain curve is above tensile curve, i.e. studied material is cyclically hardening. This is also confirmed by the curves of cyclic hardening-softening (see Fig. 5), where plastic and total strain amplitudes decrease for all stress amplitudes. The effect of cyclic hardening is more significant at the beginning of loading and from $N_f/10$ to the initiation of the magistral crack it does not change significantly, see Fig. 3.
4. The experimentally obtained dependence of stress amplitude σ_a and plastic strain amplitude ε_{ap} on the number of cycles to fracture can be adequately approximated with power regression functions and the low-cycles fatigue parameters were determined.
5. The Kohout & Věchet (K+V) function is more representative of the behaviour of Mg-alloy in the high cycle region and the Stromeyer function has a slightly higher value of the parameter S (sum of squares) which means worse fit. Fatigue limit of the studied alloy determined by the K+V function for 10^8 cycles to fracture is $\sigma_C = 53.7$ MPa.
6. The dependence of total strain amplitude on cycles to fracture can be properly fitted as the sum of plastic and elastic strain amplitudes.

Acknowledgements

Financial support of the Ministry of Education, Youth and Sports of the Czech Republic within the research project 1M2560471601 Eco-Centre for Applied Research of Non-Ferrous Metals is gratefully acknowledged.

REFERENCES

[1] BOYER, H. & GALL, T. *Metals Handbook*. American Society for Metals, 1997. ISBN: 0-87170-188-X.

[2] DRÁPAL, J., KUCHAŘ, L., TOMÁŠEK, K. & TROJANOVÁ, Z. *Hořčík, jeho slitiny a binární systémy hořčík-příměs*. Ostrava : VŠB Ostrava, 2004. 172 p.

[3] KAINER, K. U. *Magnesium Alloys and Technology*. Weinheim : Wiley-VCH, 2003, 285 p. ISBN 3-527-30570-X.

[4] EISENMEIER, G., HOLZWARTH, B., HÖPPEL, H. W. & MUGHRABI, H. Cyclic deformation and fatigue behaviour of the magnesium alloy AZ91. *Materials Science and Engineering*. 2001, A319–321, pp. 578–582.

[5] MARYA, M., HECTOR, L., G., VERMA, R. & TONG, W. Microstructural effects of AZ31 magnesium alloy on its tensile deformation and failure behaviors. *Materials Science and Engineering.* 2006, A 418, pp. 341–356.

[6] RUSZ, S., ČÍŽEK, L., Structure of Selected Magnesium Alloys Prepared for ECAP Application, Hutnické listy, č. 7, 2008, r. LXI, ISSN 0018-8069, p. 91 – 94.

[7] BUKOVINA, M. & HADZIMA, B. Vplyv mechanickej úpravy povrchu zliatiny AZ91 na elektrochemické charakteristiky. In *SEMDOK 2009, 14th International of PhD. students' seminar.* Žilina : EDIS (Žilina University Publisher), 2009. pp. 107-111. ISBN: 978-80-8070-959-4.

[8] HNILICA, F., OČENÁŠEK, V., STULÍKOVÁ, I. & SMOLA, B. The effect of structure defects on the fatigue behaviour of AZ91 magnesium alloy prepared by sand casting and squeeze casting. *Kovove mater*, 2005, Vol. 43, Nr. 4, , pp. 300–316. ISSN 0023-432X.

[9] VĚCHET, S., KOHOUT, J. & BOKŮVKA, O. *Únavové vlastnosti tvárné litiny.* Žilina : Žilina University, 2002. ISBN 80-7100-973-3.

[10] KOHOUT, J. & VĚCHET, S. New regression functions for fatigue curves. In *Proceedings of Summer school of materials fatigue '96*. Žilina : University of Transport and Communications, 1996, pp. 168-173. ISBN 80-7100-346-8 [in Czech].