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STATIC AND FATIGUE PROPERTIES OF MAGNESIUM ALLOYS USED IN AUTOMOTIVE INDUSTRY

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Abstract: *In trying to improve the performance of automotive components the use of a new class of materials as AZ80 and ZK60 is investigated. Static tests (tension, compression, torsion) reveal interesting behaviour and failure modes of specimens. Fatigue tests on the intermediate and long life of such materials are done on specimens with reduced size, according to standards. Fatigue tests reveal scatter of results, attributed to specimen manufacturing and material quality. For ZK60 an S-N curve is established and comments on the hysteresis loops are done. A possible complete approach on characterizing magnesium alloys give confidence in the future design of automotive structural components with high resistance and reduced weight.*

Keywords: magnesium alloys, static and fatigue tests, S-N curve, fatigue limit

INTRODUCTION

The main market for forged components is the automotive industry (around 58% from total). The forging industry is thus faced with some particular trends that relate to developments within this sector [1], [2].

The general platform strategies, as well as the increase in diesel-engine powered cars and four-wheel driven sports-utility vehicles are implying a volume increase for forged components. Further, the automotive industry has committed itself to substantially reduce fuel consumption and exhaust emissions (amongst others CO_2), for which weight saving at all levels is crucial. Priorities in lightweight structure design are the un-sprung mass (wheels and their suspension), the front end before the front axle and the mass between the front axle and instrument panel. All these are typical areas where forged components are used.

In this respect, it is increasingly recognized that aluminium (with a density of 2,700 kg/m^3) and magnesium (1,800 kg/m^3) are attractive alternatives for steel (7,800 kg/m^3). Notably magnesium is the lightest available engineering metal, being 75% lighter than steel and 35% lighter than aluminium.

Looking to the specific property values, benefits are anticipated for strength-related and in particular for bending-relevant parts, with a potential gain for magnesium of up to 37% over aluminium. As an example of the trend towards lightweight design for structural transport applications, the front-wheel suspension of a *Jaguar XJ* model contains several aluminium components with a total weight of only 17 kg.

For magnesium, warm forging is required because of its metallurgical constitution. Relevant expertise in this area is as yet limited with only few industrial applications for low-volume specialty products [1], [2]. Current restrictions are as follows:

- underdeveloped mechanical properties as compared to aluminium for the commercially available magnesium alloys, including large variations in material quality in and between batches;
- exemplary knowledge on the material-specific aspects of forging (process windows, temperature and material flow control, etc.) based on handcraft rather than on scientific insights, and non-optimized machining (cutting tools, process windows,) for subsequent finishing;
- offset of the inherent weight-saving potential by using heavier component designs, due to the previous reasons.

To unlock the potential of magnesium for the forging sector, its customers and the eventual end-users, these impediments need to be cleared and the resulting technologies transferred and communicated to the stakeholders.

TESTED MATERIALS

Extruded alloys as AZ80 and ZK60 were tested up to now. For AZ80 two grades were available: AZ80A-T5 extruded delivered in bars with a diameter of 28 mm, and AZ80A-F extruded delivered as 5 mm diameter wires. The ZK60 was delivered as large diameter bars from which were cut flat specimens according to standards. Forged components will be tested soon.

The AZ80 alloy was studied by: 1) optical microscopy (OM) on Olympus BX60M microscope; 2) electron microscopy (EM) on ESEM (ecological) with EDS microscope.

The microstructure of the 28 mm bars is first analysed by OM. In a longitudinal section – parallel to the axis of the extruded bars – the surface was prepared by exposing it to 4% Nital during 20 seconds. One can notice spherical precipitates, of globular type, and size about 5-20 μm, as shown in Figure 1. In a transversal section a cellular structure with nonuniform precipitates of about 10-20 μm can be noticed (Figure 2). In each of the two figures there are two magnifications, the scale being represented in the low-right corner.

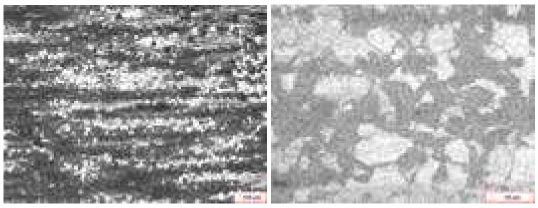


Figure 1: Longitudinal section in a 28 mm diameter bar

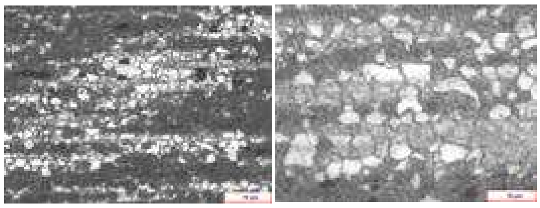


Figure 2: Transversal section in a 28 mm diameter bar

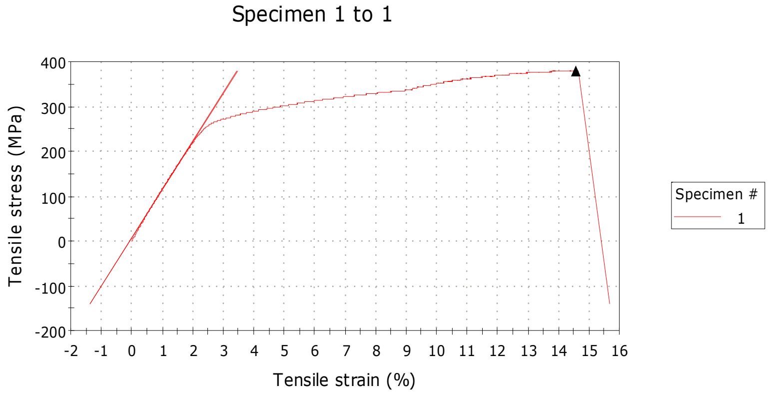
STATIC TESTS

Tension, compression, and torsion tests were done for both grades of AZ80A material. Values to be established were considered as: *E* – longitudinal modulus of elasticity (Young's Modulus); *G* – transversal modulus of elasticity; *ν* – Poisson's ratio; R_m – ultimate strength; $R_{p\ 0,2}$ – offset yield limit (0.2 % offset yield stress); *A* – elongation at failure.

The following standards were followed: *ASTM B557-06*: Standard Test Methods for Tension Testing Wrought and Cast Aluminum and Magnesium-Alloy Products and *ASTM E8M-04*: Standard Test Method for Tension Testing of Metallic Materials [Metric].

Not all details are going to be presented here. Five specimens of diameter 4 mm in the calibrated part and gage length of 50 mm have been tested on a Lloyd Instruments testing machine with the nominal load of 100 kN; the experimental values were analysed with the software NEXIGEN Plus. The average values are: E = 44530 MPa, R_{m} = 350 MPa, $R_{\mathrm{p\ 0,2}}$ = 248 MPa, A = 9,9 % . Failure is produced in a plane inclined with 45^{o} with respect to direction of loading indicating that deformations are produced in the material through shearing. This behaviour is expected to be produced also at the failure in compression.

Three more tension tests were done on specimens made from a 28 mm bar as having the nominal diameter of 12.5 mm (1/2 of an inch). This is recommended in the *ASTM E8M-04* standard. This time a 100 kN INSTRON 8801 hydraulic testing machine was used, together with an Instron extensometer of 50 mm gage length. A conventional characteristic curve, as plotted by the Bluehill software, is represented in the next figure (Figure 3). For metals it is recommended to calculate the E-modulus or the metal matrix modulus (the way of calculating them is explained in the reference manual of the testing machine). Both values are included for comparison in an appropriate table.



Specimen	Ultimate Tensile Strength [MPa]	Modulus (E-modulus) [MPa]	Modulus (Metal Matrix) [MPa]
1	379.9	43270	42997

Figure 3: Tension test for AZ80A T5 (specimen 2)

This time the ultimate tensile strength is in between 373 and 380 MPa, values a little bit higher than the ones established for wires. The as calculated E-modulus is in average about 43217 MPa and the metal matrix modulus is about 42566 MPa. The differences from the previously established values are small, and probably indicate a specimen dependent behaviour. For comparison, for the extruded alloy AZ80A-T5, were mentioned [3] the average values of the same parameters as: E = 45000 MPa, G = 17000 MPa, ν = 0,35, R_m = 380 MPa, $R_{p\,0,2}$ = 275 MPa, A = 7 % . The ultimate strength R_m is practically the same as for our tests for the 12.5 mm bar and higher than the one obtained for the 4 mm wire (as 350 MPa). The longitudinal modulus of elasticity is in average E = 44530 MPa for wires (five tests) and 42566 MPa for bars (three tests), both values being a little bit smaller than the indicated value of 45000 MPa. However, the experimentally established value of the elongation at break is in average 9.9 % for the wires and 13.2 % for the bars, that is greater than the 7 % given in [3].

For extruded ZK60 the static tension tests were done on a Walter-Bai testing machine of 6.3 tf and followed ASTM E8M-04: Standard Test Method for Tension Testing of Metallic Materials [Metric] and the following average values were obtained: Young's modulus E = 43.6 GPa, ultimate strength R_m = 280.3 MPa, and offset yield limit $R_{p0,2}$ = 136 MPa. The elongation at failure measured with an Epsilon 3542 extensometer as A = 16,82 %.

FATIGUE TESTS

Not too much information is available in the literature for establishing fatigue properties of magnesium alloys. A compilation of existing fatigue and fatigue crack growth data of different Mg-alloys has been published by ASM International [4]. One can underline that fatigue properties of some of the studied Mg-alloys are very good. Fatigue limits (on base of 10^8 cycles) up to approximately 100 MPa (for AZ63, AZ91, AZ92) are reported for cast Mg-alloys after appropriate production and heat treatment and fatigue limits up to 130 MPa (AZ31 and AZ80) for wrought Mg-alloys under cyclic axial loading. Coming back to [3], only for the forged AZ80A-T6 is indicated a fatigue strength of 100 MPa at 10^6 cycles, no other details being given.

The influence of extrusion temperature on fatigue performance of AZ80 and ZK60 magnesium alloys is given in [5]. They performed fatigue tests on electrolytically polished hour-glass shaped specimens in rotating beam loading (R = -1) at a frequency of 50 Hz in air. Zenner and Renner

[6] have investigated the cyclic deformation behaviour in strain controlled tension-compression tests. The magnesium die casting alloys AZ91 and AE42 and the magnesium extrusions AZ31 and AZ80 are tested. They emphasize that the magnesium extrusions show a totally different behaviour in tension and in compression; that is the hysteresis in experiments differs from the calculated hysteresis for the cyclic stress-strain curve.

As being at the beginning of our tests, we try to keep the initial testing conditions quite simple. That is we avoid for the extruded AZ80 the anisotropic deformation behaviour in the direction of tension and compression, and we perform axial fatigue tests in tension-tension with a force controlled constant amplitude. We follow standards *ASTM 466-96*: Standard practice for conducting force controlled constant amplitude axial fatigue tests of metallic materials, *ASTM 468-9*6: Standard practice for presentation of constant amplitude fatigue test results for metallic materials, and *ASTM 606-80*: Constant amplitude low cycle fatigue testing.

4.1 Tests for AZ80

The low cycle fatigue domain was considered as important at this stage and a constant average force was imposed for all tests done at two frequencies: 25 Hz and 10 Hz. The AZ80-F wires of initial 5 mm diameter were used in order to make specimens of reduced size, with a reduction of the cross section to about 3.2-3.8 mm in the middle. About 20 specimens of this shape were tested up to now [7]. Their fixture is shown in Figure 4. Around five specimens broke at the limit of fixture towards two pressing collars which are threaded into the grips of the Instron 8801 testing machine. Few other tests were done on AZ80A-T5 specimens of reduced size (but according to *ASTM 466-96*) which were directly threaded into the grips of the testing machine as shown in Figure 5. The shape is hour-glass and the diameter is 6 mm.

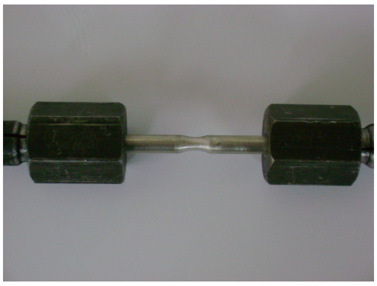


Figure 4: Specimen made from AZ80A-F

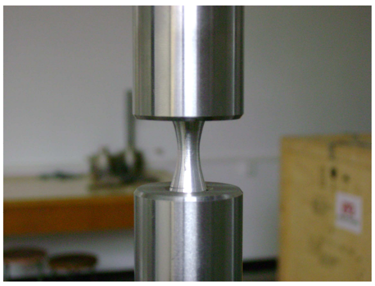


Figure 5: Specimen made from AZ80A-T5

As mentioned a constant average force of 1800 N was applied for the AZ80A-F specimens made from wires. This gives a tensile stress in between 224 MPa and 159 MPa (diameter in between 3.2 mm and 3.8 mm) – that is in average 192 MPa. By considering the ultimate tensile strength σ_u = 350 MPa (as obtained through static tests) we are in between 0.64 and 0.45 from σ_u. A crude but simple approximation as to establish the fatigue strength σ_f would be the relation $\sigma_f = 0.5\sigma_u = 175$ MPa. This just means that as the average stress is higher than the presumed fatigue limit. We may assume that a low cycle fatigue life domain will prevail.

The amplitudes of the sine loading are chosen to be 600, 500 and 400 N. Only one test was done for an amplitude of 200 N, but the specimen didn't break. Although the test is done for force controlled constant amplitude there are some small differences in between the theoretical maximum and minimum imposed forces and the experimental ones, for which the test is performed. Table 1 summarizes the obtained data. Only reliable tests have been analysed.

Table 1: Number of cycles till failure for AZ80A-F as a 4 mm wire

Freq. [Hz]	Amplitude [N]	Test no.	Diameter [mm]	F_{max} [N]	F_{min} [N]	Max. stress [MPa]	Min. stress [MPa]	Cycles till failure
25	600	3	3.2	2343	1219	291	152	18346
		4	3.15	2381	1223	306	157	20574
		11	3.55	2384	1219	241	123	35893
	500	15	3.70	2296	1312	214	122	46681
		17	3.55	2277	1334	230	135	40845
		19	3.62	2296	1314	223	128	88666*
		21	3.62	2276	1332	221	129	128173*
	400	8	3.40	2201	1399	242	154	132113
10	600	5	3.25	2365	1178	285	142	22593
		6	3.15	2398	1204	308	155	12665
		12	3.50	2364	1171	246	122	40303
	500	16	3.80	2317	1292	204	114	77460
		18	3.60	2305	1303	226	128	82351
		20	3.76	2305	1303	208	117	32913**
	400	9	3.55	2207	1395	223	141	1768671

* additional surface polishing of the middle section of the specimen
** unreliable result – probably failure due to inhomogeneous material

As one can notice there is quite a significant scatter of data. First of all the diameter of the wire in the central part differs from 3.15 mm to 3.80 mm, with an increase of almost 21 %. Correspondingly the values of the maximum and minimum stresses are different for the same stress amplitude and the number of cycles till failure change. We wouldn't rely on the obtained results for test no. 19 and test no. 21 where an additional surface polishing looks to have contributed as giving a significant increase of cycles till failure.

4.2 Tests for ZK60

Present part of the research concentrates on the fatigue behaviour of the ZK60 extruded magnesium alloy. We follow same standards as mentioned before.

Fatigue testing is done by using a 5 tf (6.3 tf in static testing) Walter-Bai servo-hydraulic machine at a frequency of 10 Hz. Hour-glass specimens machined according to the standard were tested in force control in reversed loading. High cycle fatigue domain is considered hereby.

The force amplitude was decreased in consecutive tests from 11 kN to 5.3 kN as to obtain stress amplitudes from about 160 MPa to 75 MPa as shown in Table 2.

Table 2: Fatigue data obtained for ZK60 alloy

Test no.	Force ampl. [kN]	Max. stress [MPa]	Min. stress [MPa]	Cycles till failure
1	10.37	157.61	-156.16	20897

3	10.64	149.99	-154.36	20744
11	10.50	148.4	-150.23	22176
12	11.00	147.36	-148.02	28702
10	9.81	140.38	-143.81	28203
18	9.67	140.27	-140.27	40376
19	9.83	143.74	-146.31	23038
2	9.43	134.43	-138.56	22536
6	9.31	130.28	-136.14	59723
21	9.31	130.18	-133.95	54828
13	9.00	124.52	-124.8	84687
14	9.10	125.39	-125.66	60409
22	8.67	120.04	-119.90	35500
25	8.70	122.63	-122.49	137636
15	7.40	100.36	-101.17	811692
16	7.15	100.58	-100.44	1246045
17	5.30	75.80	-75.37	6453095

The corresponding S-N curve is represented in Figure 6. Although not too many data are available up to now, we may suggest that a reasonable value for the fatigue limit could be 100 MPa.

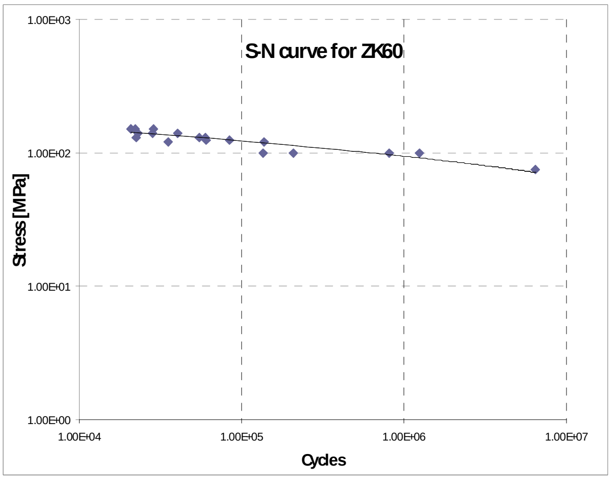


Figure 6: Plot of data for obtaining the S-N curve of extruded ZK60

Some SEM analyses revealed that this material contains mangan and titanium, although it should be 98 % magnesium and 2 % zirconium and silicium. As seen in Figure 7 voids are inevitable.

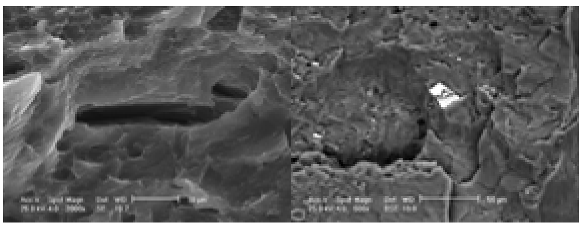


Figure 7: SEM analyses of ZK60

However, another test with an amplitude of 75 MPa didn’t lead to the failure of the specimen. It is interesting to monitor the histeresis loops during each test. Just as an example, in Figure 8 the first 100 cycles, the middle 100 ones, and the last 100 cycles are shown.

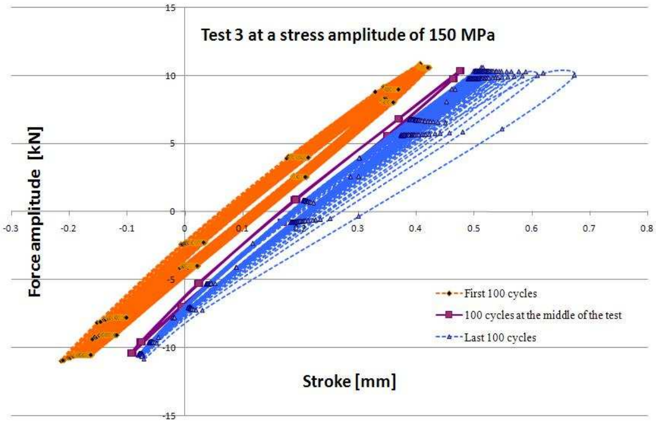


Figure 8: Histeresis loops obtained during a test at an amplitude of 150 MPa

CONCLUSIONS

The frequency of testing has a clear influence on the fatigue response of the AZ80A-F material, especially when the amplitude is not as big as to give a very short fatigue life. However, for the moment, not enough data are available to explain better the obtained results and make pertinent observations on the fatigue strength of the magnesium alloy AZ80A by taking into account the influence of the average stress and the frequency of testing.

The ZK60 extruded magnesium alloy shows a fatigue limit of about 100 MPa. Interesting observations can be done on the damage through the histeresis loops. The cyclic behaviour of the material stabilizes at midlife, and important deterioration is noticed just before failure.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

[1] M.M. Avedesian, H. Baker (editors) – *Magnesium and Magnesium Alloys*, ASM International, Materials Park – Ohio, USA, 1999

[2] R.S. Busk, *Magnesium Products Design*, Marcel Dekker, New York, 1987

[3] www.matweb.com – MatWeb, Your Source for Material Information

[4] S.D. Henry, G.M. Davidson, S.R. Lampman, F. Reidenbach, R.L. Boring, W.W. Scott, Jr. (editors) – *Fatigue Data Book: Light Structural Alloys*, ASM International, Materials Park - Ohio, USA, 1995

[5] M. Shahzad, D. Eliezer, W. Gan, S. Yi, L. Wagner – *Influence of Extrusion Temperature on Microstructure, Texture and Fatigue performance of AZ80 and ZK60 magnesium alloys*, Materials Science Forum, Vols. 561-565, p. 187-190, copyright Trans Tech Publications, Switzerland, 2007

[6] H. Zenner, F. Renner – *Cyclic Material behaviour of Magnesium Die Castings and Extrusions*, International Journal of Fatigue, Vol. 24, p. 1255-1260, 2002

[7] D.M. Constantinescu, P. Moldovan, W. Sillekens, M. Sandu, G. Popescu, F. Baciu – *Fatigue life particularities of AZ80 magnesium alloys used in automotive industry*, 2nd Fatigue Symposium, Leoben, Ed. W. Eichlseder, p. 117-127, 2008