FATIGUE-CRACK-PROPAGATION OF SUPERLIGHT Mg-Li BASE ALLOYS

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This paper is presenting results on fatigue properties of superlight magnesium-lithium-X alloys (X = Al, Zn, Zr etc.) with more than 30 at% lithium content. Significant advantages such as densities up to 30% below commercial magnesium alloys, e. g. AZ 91 HP, still make the attraction of bcc alloys. The influence of different factors (e.g. frequency, environment) on crack propagation in precipitation hardened alloys with different chemical composition and microstructure has been studied. The addition of third elements leads to new features in the microstructure. As an example may serve the MgLi40Al-system, which facilitates the formation of the phase AlLi. The results of fatigue testing are integrated in a special microstructural model, which allows correlation between microstructure and fatigue crack formation and -propagation.

INTRODUCTION

In all fields of technology where masses are being extremely accelerated, materials are demanded which fulfil high weight-specific properties, high consistence and stiffness and a density as low as possible. The crack growth behaviour of magnesium alloys, which as a result of the low specific gravity are being used more and more frequently in many branches of technology, has been studied insufficiently, especially in case of the lighter magnesium-lithium alloys. Only in individual cases the fracture toughness of magnesium alloys in static loading has been determined and the development of fatigue cracks been investigated (1). At the moment, the use of bcc crystal Mg-Li alloys with contents of lithium above 30 at% is very restricted even though there is the possibility to use metallic materials with densities below 1,5 gcm^{-3}. This paper investigates the fatigue behaviour of different superlight Mg-Li-alloys, which are strengthened by incoherent stable AlLi-precipitation. An explanation for the unsatisfactory thermomechanical and chemical behaviour of bcc Mg-Li base alloys is the segregation process of lithium caused by coordination tendencies of Mg-Li in combination with a high lithium diffusibility which is additionally accelerated by deformation.

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In microstructural areas with lithium concentrations above 55 at% relaxation processes can take place at room-temperature. Therefore the reduction of lithium diffusion has to be the most important task. In this relation one possibility is the addition of lithiumaffine elements, e.g. Al, Zn, H.

EXPERIMENTAL PROCEDURE

Materials

The Mg-Li cast material is produced in a vacuum/inert-gas induction furnace. The alloys are being melted in an Armco iron crucible and then intensively homogenized. After consolidation the cast materials were homogenized at 400°C for 30 minutes and quenched in oil. Furthermore the alloys are either aged or extruded at different temperatures (100°C and 300°C) with partial heat treatment at 200°C for four hours. Based on a binary MgLi40 at% alloy with high ductility and low tensile strength the addition of 3 respectively 6 at% of aluminium causes a rapid increase of strength. A thermomechanical treatment of homogenized specimens is being able to improve the mechanical properties of superlight MgLi-alloys (2), fig. 1.

Stable crack growth evaluation

The in-situ crack-growth measurement was performed by using the potential drop method with alternating current. To investigate the stable crack growth of the material a microprocessor controlled universal servo-hydraulic testing machine has been used. The specimens were single edge notch bend specimens. For identifying the dynamic fatigue behaviour crack formation and crack propagation tests were made in different environments (dry air, labatory air and argon) and frequency loading (10 Hz; 0,1 Hz). Fatigue crack growth tests were conducted at a high stress ratio (R = 0,7) to reduce possible effects due to crack closure.

RESULTS - FATIGUE BEHAVIOUR

Crack growth behaviour under cyclic loading

The variation of fatigue crack growth rate (da/dN) with the cyclic stress intensity factor (ΔK) for two different thermomechanically treated MgLi40Al6 alloys is shown in fig. 2. The thermomechanical treatment of homogenized specimens is being able to improve the dynamic behaviour. The finely dispersed AlLi-precipations may be responsible for the best dynamic behaviour of thermomechanically treated MgLi40Al6 alloys. The reason for the different dynamic properties is the formation of the structure, fig. 3. However materials with high alloying contents strongly tend to suffer from intergranular embrittlement caused by the nucleation of precipitations at grain boundaries and the thermically activated formation of particle free zones (PFZ). Fatigue-crack propagation rates in the thermomechanically treated alloy, at 300°C and R = 0,7, are approximately one order of magnitude faster than in thermomechanically treated alloy at 100°C, at equivalent ΔK levels. In most cases a thermomechanical treatment at 100°C is more favourable than a handling at 300°C. Figure 4 shows the influence of different environments on the crack growth behaviour of MgLi40Al6 (TMT 100°C). The results confirm that the environment has a considerable influence on the fatigue properties of the investigated alloys. A comparison of fatigue crack growth curves shows that in dry air the crack velocity is more than one decade lower relative to lab air (relative humidity 55%). The crack growth rates at R = 0.7 for f = 10 Hz and f = 0.1 Hz are shown in fig. 5. At the lower frequency of 0.1 Hz the plot of ΔK shows a large increase in crack growth rate.

Microstructural Model

The identification and modelling of the principal damage, failure, and toughening mechanisms are relatively advanced, particularly with respect to those that contribute to mechanical properties under noncyclic loads. Receiving more information about fatigue properties of superlight Mg-Li40 at% alloys the fatigue results are integrated in a special microstructural model. The influence of microstructure on fatigue crack growth in Mg-Li40 at% alloys is essentially not unlike other precipitation hardening alloys except the high lithium diffusibility. The developed model is subdivide in two different sections. In the first section the general influence of different parameters is presented. In the second section some mathematical relations between microstructure and fatigue properties (ΔK_o, ΔK_c) is shown. The influence of different microstructural effects during crack growth from Mg-Li40 at% alloys is shown in fig. 6. The addition of third elements (e. g. Al, Zn) leads to new features in the microstructure. The most finely dispersed AlLi-precipitations are responsible for the shift of the fatigue curve to higher ΔK values. Some results of fatigue crack propagation tests are summarised in Table 1. The C and n coefficients of the Paris law relationship have been evaluated from a mean curve obtained by two or more tests at the same R (R = 0.7) value:

$$da/dN = C^*\Delta K^n \quad (1)$$

Alloy	C	n	ΔK_o ($Nmm^{-3/2}$)	ΔK_c ($Nmm^{-3/2}$)
MgLi40	$3{,}68*10^{-6}$	0,63	35	105
MgLi40Al3	$6{,}09*10^{-7}$	0,92	45	150
MgLi40Al6	$4{,}78*10^{-8}$	1,34	65	193

Table 1: Fatigue properties for Mg-Li40at%-X alloys, TMT 100°C, f=10 Hz, Air

Based on a binary Mg-Li40 at% alloy with low fatigue properties the addition of 3 respectively 6 at% of aluminium causes a rapid increase of threshold value and the maximum stress intensity factor under cyclic loading. The parameter C decreased and the parameter n increased with increasing aluminium content. The parameters ΔK_o, ΔK_c for at 100°C thermomechanically treated Mg-Li40at%-X-alloys can expressed as a function of aluminium (at%) content.

$$\Delta K_o = 5\,(at\%Al) + 35 \quad (2)$$
$$\Delta K_c = 15\,(at\%Al) + 105 \quad (3)$$

The number, distribution and types of metastable and stable phases that may be present in superlight Mg-Li40 at% alloys is a complex function of composition, aging time and temperature, quench path, degree of recrystallisation and grain morphology. Homogenization of strain is favoured by the precipitates which cannot be sheared by the dislocations. The stable AlLi-precipitations (formation over incoherent metastable $MgLi_2Al$-precipitation) are incoherent, not shearable and have dispersoid structure (4). The intermetallic AlLi-phase (ordered B2 structure) is not to be deformed macroscopilly and increases the flow stress of the Mg-Li-Al alloys by dispersion strengthening. A higher volume fraction of the AlLi-phase causes micro cracks in the structure during deformation (4). The thermomechanical treatment of MgLi40Al3 at 300°C leads to a pronounced subgrain formation with favourable dynamic properties. A reduction in grain size decreases the slip length and reduces the stress concentration at grain boundary when the deformation is localised within the matrix or PFZ. Fine equiaxed grains also enhance cross slip that produces a homogeneous deformation. In general a thermomechanical treatment of Mg-Li alloys by 100°C leads to better dynamical properties. The thermically activated formation of large particle free zones and the nucleation of precipitations at grain boundaries is responsible for low ductility and fracture toughness.

SUMMARY AND CONCLUSIONS

The present results confirm a considerable increase of fatigue properties of superlight Mg-Li base alloys by alloying aluminium and zinc in combination with an optimised thermomechanical treatment. The thermomechanically treatment of homogenized specimens is able to improve the crack initiation and crack propagation in Mg-Li40 at% alloys. But up to now the high diffusion of lithium, regarded as the basic destabililizing mechanism, could not have been reduced effectively. At the development of Mg-Li40 at%-X alloys a dispersion hardening with non-soluble or reactive solids (e. g. Si, Ca, Zr) or gases (e. g. H) must be integrated. In this paper, a special microstructural model of material fatigue has been developed. The model describes the correlation between microstructure and fatigue.

ACKNOWLEDGEMENT

On July 1st 1990 the German Science Foundation (DFG) established a research team called "Forschergruppe" consisting of 5 projects at 3 different institutes with the main objective to expand the application potential of b.c.c Mg-Li-X materials with densities below 1,5 gcm^{-3}. The results base on the work of the group.

SYMBOLS USED

a	= notch-length (mm)
C,n	= Paris-parameter
Δa	= crack growth (mm)
ΔK_o	= threshold value of crack growth under cyclic loading ($Nmm^{-3/2}$)
ΔK_c	= maximum stress intensity factor ($Nmm^{-3/2}$)
f	= frequency (Hz)
N	= number of cycle
R	= stress-Ratio
TMT	= thermomechanically treatment

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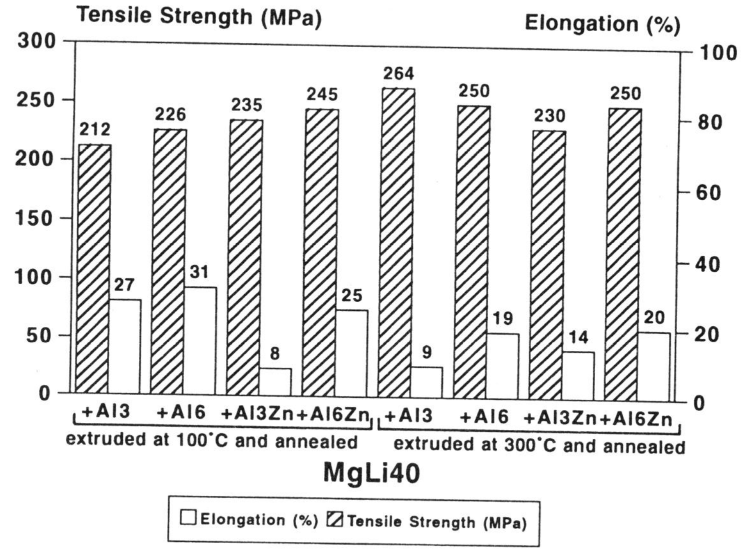

Figure 1 Tensile strength and elongation of investigated alloys (2)

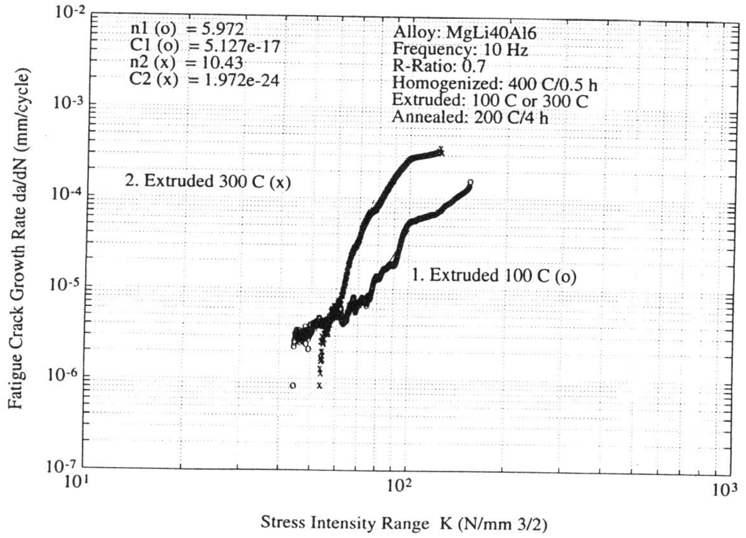

Figure 2 Influence of thermomechanically treatment on Mg-Li40Al6 alloys

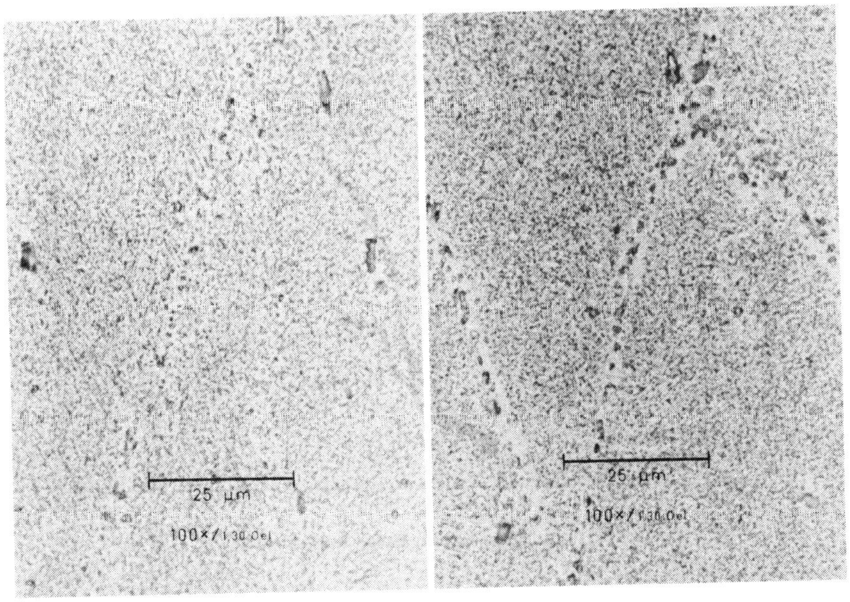

Figure 3 Mg-Li40Al6 extruded at **100°C** Mg-Li40Al6 extruded at **300°C**

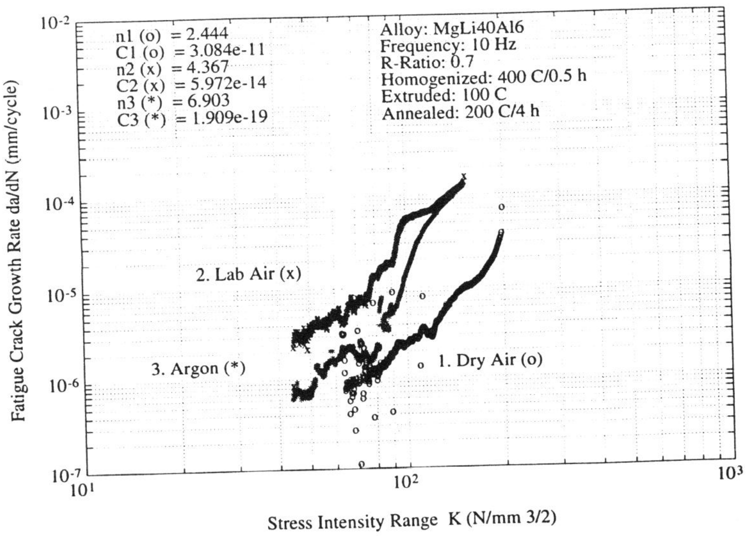

Figure 4 Influence of environments on the stable crack growth

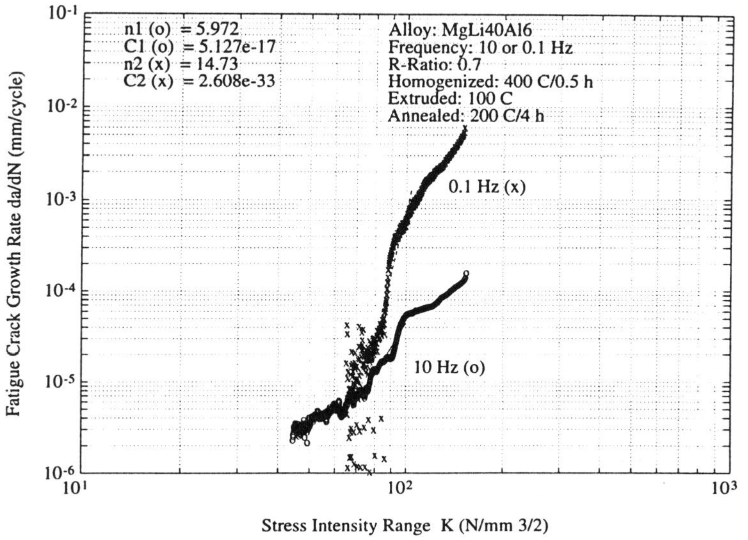

Figure 5 Effect of frequency on crack growth rate

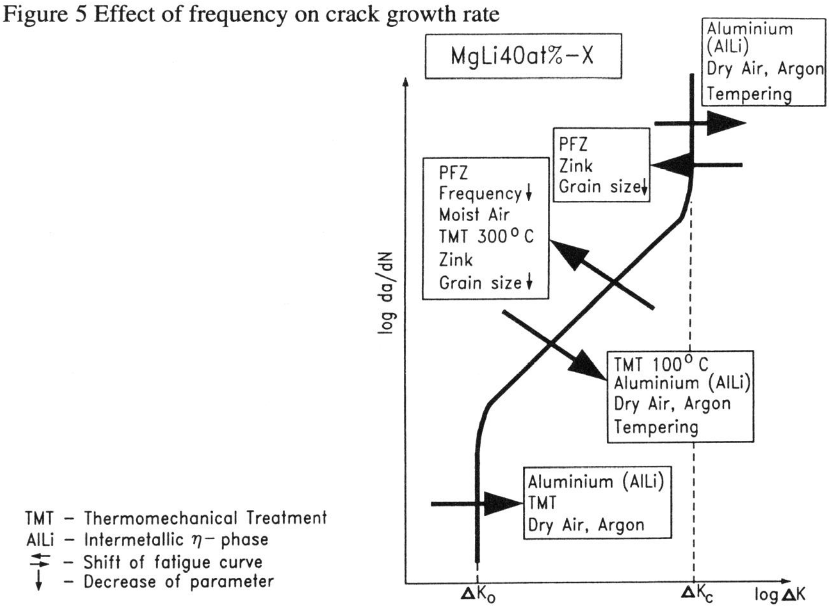

Figure 6 Microstructural effects on stable crack growth of Mg-Li40at%-X-alloys