Damping behaviour of AZ91 magnesium alloy with cracks

Jürgen Göken¹, Werner Riehemann*

Institut für Werkstoffkunde und Werkstofftechnik, TU Clausthal, Agricolastrasse 6, D - 38678 Clausthal-Zellerfeld, Germany

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Abstract

The amplitude-dependent damping of a commercial magnesium cast alloy AZ91 was determined at room temperature by measurement of the logarithmic decrement of free decaying vibrations of bending beams clamped at one side. In order to generate cracks in the specimens they were subjected to (1) isochronal heat treatments for 1 h at temperatures above 400 °C with succeeding quenching in cold water and (2) controlled fatigue bending loading in the same equipment also used for the damping measurements. After both treatments, the amplitude-dependent damping curves show a maximum for strains 10⁻⁵ to 10⁻³, which can be correlated with the presence of cracks and can be explained by a simple rheological model based on crack damping. This maximum is enhanced when the number of loading cycles or the quenching temperature is increased which can be explained by crack nucleation. Crack growth with increasing number of loading cycles shifts the maximum to lower strains.

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1. Introduction

It is well known that cracks can have an essential mostly audible influence on the resonant oscillations of components in machines and buildings. This is due to the change of the elastic moduli and the damping of engineering materials by cracks and can be utilised, e.g. in component testing (see, e.g. [1]). In spite of the obvious technical importance of these effects, systematic investigations of the crack influence on internal friction of engineering materials are extremely rare.

For the present work the influence of cracks in the commercial magnesium cast alloy AZ91 on its amplitude dependent damping and Young’s modulus both at room temperature have been measured and evaluated. AZ91 is the most common cast magnesium alloy. It is widely used due to its high specific strength at room temperature, low cost and availability. For the present investigation, AZ91 is particularly suitable due to its poor fatigue strength [2] and hot crack sensitivity [2,3].

2. Experimental

For damping measurements rods 125 mm long with circular cross section of 10 mm diameter were milled from AZ91C (nominal composition: 8.1–9.3 wt.% Al, 0.4–1.0 wt.% Zn, 0.13–0.35 wt.% Mn, rest Mg) cast bars. One end of the rods was machined to bending beams 89 mm long, 10 mm wide, and 3 mm thick. The thicker circular end of the samples about 30 mm long was clamped in the sample holder. Thus external friction could be inhibited.

Damping was measured in vacuum (60 Pa) in terms of the logarithmic decrement δ of free decaying bending beam vibrations. The bending beams fixed at one end and a permanent magnet attached at the free end dipping into a coil system were contactlessly excited to mechanical resonance of their fundamental vibration (clamped-free-bar with end loading) by an alternating magnetic field. This was realised by a closed feedback loop consisting of an excitation coil, an induction coil and a power ac amplifier. When the amplifier was cut from the coil system at given amplitude by relays, the free decaying vibration was measured via the effective alternating voltage induced by the moving permanent magnet into the induction coil. It has to be stressed that this method allows the measurement of amplitude-dependent internal friction for a single individual decay of free vibration.
The experimental setup is described in detail elsewhere [4,5]. All measurements were done at room temperature. Resonant frequencies ranged from 65 to 85 Hz.

The AZ91 specimens were heat treated in glass tubes containing argon with a pressure of about $10^5$ Pa. Homogenisation was performed in two different ways: (1) at $530\,^\circ\mathrm{C}$ for 100 min with subsequent cooling of the glass tubes with the samples inside in air and (2) at $413\,^\circ\mathrm{C}$ for 24 h with subsequent quenching of the sample without glass tubes in water. It was tested that both homogenisation treatments do not produce significant cracks. After heat treatments at lower temperatures the bending samples were quenched in water in order to freeze in the microstructure or generate thermal cracks.

Mechanical cracks were also produced by controlled fatigue bending loading of the bending beam samples in the same apparatus also used for the damping measurements controlling the amplitude and number of vibrations.

3. Results

In an earlier investigation, a characteristic change of damping versus strain curve of AZ91 by thermally induced cracks was found [3]. For medium strains in the order of $10^{-4}$, a maximum in damping developed with increasing quenching temperature. For bulk magnesium alloys (without cracks) the damping is strain independent at these low strains [6]. In Fig. 1, the logarithmic decrements at $10^{-4}$ maximum strain amplitude of AZ91 in as-cast and in homogenised ($413\,^\circ\mathrm{C}, 24\,\mathrm{h}$, water quench) state are plotted versus the annealing temperature for isochronal heat treatments. Besides of two small maxima being due to precipitation processes [3], a steep increase of damping for temperatures higher than the homogenisation temperature ($413\,^\circ\mathrm{C}$) can be observed for both specimens. This is accompanied by a not so steep decrease of the elastic modulus. The rapid change can be correlated with the appearance of cracks becoming visible in SEM micrographs. The cracks can be attributed to quenching producing high temperature gradients in the AZ91 samples due to their low thermal diffusivity. This leads to stresses sufficient for nucleation or growth of cracks due to the high thermal expansion of magnesium alloys. For damping and modulus (cf. Fig. 1), the homogenised sample shows a more rapid change than the cast one. This can be explained by the lower thermal conductivity and therefore higher temperature gradients in the homogenised material.

Cracks can also be produced in most materials by fatigue treatment. With cast AZ91 samples, that were also used for damping measurements, bending fatigue tests and additional heat treatments were performed in order to study the effect of mechanical cracks on the strain dependent damping and Young’s modulus. In Fig. 2, the damping results are presented. It can be seen that before a critical number of cycles to fatigue of about $2\times10^5$ (− and + symbol in Fig. 2) the amplitude-dependent internal friction curves show the typical behaviour of magnesium alloys that can be characterised by a strain independent damping range at lower and stress dependent damping mostly due to get away of dislocations from weak pinning points at higher stresses, that can be described by the theory of Granato and coworkers [6,7]. After $2\times10^6$ cycles (× symbol in Fig. 2), the amplitude-dependent internal friction curve has shifted a little to higher damping especially at medium strain levels. Only $5\times10^6$ cycles more (altogether $2\times10^7$ cycles, open circle in Fig. 2) shifts the curve dramatically and a
Fig. 2. Logarithmic decrement of bending vibrations of as-cast AZ91 after various fatigue and heat treatments (homogenisation with 530 °C, 100 min, air cooling) plotted vs. maximum strain of the bending amplitude (amplitude dependent internal friction curves). The curves are fitted to the measurements according to Eq. (3).

Fig. 3. Young’s modulus after various fatigue and heat treatments also occurring in Fig. 2.

maximum at about \(2 \times 10^{-4}\) develops. Subsequent annealing at 530 °C for 1 h (filled circle in Fig. 2) shifts the curve back to lower damping being not that low as the initial ones and shifts the maximum to smaller strains. This behaviour can be repeated by renewed cycling-annealing sequences in which the maximum shifts to lower strains due to cycling (open symbols in Fig. 2) and the damping decreases due to heat treatment (closed symbols in Fig. 2) the longer it is performed.

The evolution of Young’s modulus for the same thermo-mechanical treatments is shown in Fig. 3. Similar to damping the modulus decreases for more than about 2,140,000 cycles.

Contrary to damping this happens more monotonously and is mainly affected by the number of vibrations and is not that much recoverable.

4. Discussion

Many experimental results indicate the crack origin of the high damping measured at low strains in the order of \(10^{-4}\). This can not only be detected for magnesium alloy AZ91 investigated in the present paper and in [3], but also for other crack sensitive materials like foams [8,9].
1. After critical number of cycles to fatigue damping increases with further increasing number of cycles, damping also increases when cracks are introduced by thermal stress [3].

2. After increase of damping due to cycling to fatigue or thermally stressed specimens cracks can be observed in the exposed specimens by SEM [3, 9].

3. Young’s modulus decreases simultaneously with the increase of damping.

4. The samples break in the end after increase of damping or decrease of modulus and continued cycling.

Therefore, a simple rheological model taking into account the crack origin of damping is presented here. By approximation, one elementary crack is assumed to be represented by a frictional grip which is attached in series to a spring $E_i$ (cf. Fig. 4). This frictional grip is absolutely firm for stresses smaller than its critical stress $\sigma_{ci}$, operates at this stress and is separated for higher stresses. Then the spring $E_i$ can not take stress any more and only another spring attached parallel to this arrangement, representing the relaxed modulus $E_r$ of the solid with opened cracks elongates. $E_i$ also transforms the critical stress $\sigma_{ci}$ into critical strain $\varepsilon_{ci}$ via $\sigma_{ci} = E_i \varepsilon_{ci}$. In this process the elementary crack opens at the critical strain and the mechanical energy $\Delta W$ is converted to heat by the displacement of the two crack surfaces (cf., e.g., [10]), by emission of dislocations at the crack tips (cf., e.g., [11]), or by crack growth. Therefore, the dependence of the internal friction of the strain for this elementary process is

$$IF_e \equiv \frac{\Delta W}{W} \approx \frac{E_i}{E_r} \left( \frac{\sigma_{ci}}{\sigma} \right)^2 \propto \left( \frac{\varepsilon_{ci}}{\varepsilon} \right)^2, \quad \text{for } \varepsilon \geq \varepsilon_{ci}$$

and

$$IF_e = 0, \quad \text{for } \varepsilon < \varepsilon_{ci}$$

(1)

$W$ is the mechanical energy. The cycled to fatigue samples have a lot of cracks with various lengths and various orientations which can be represented by the same number of serial frictional grip-spring arrangements all attached in parallel to the spring representing the relaxed modulus. It is assumed that this variety of cracks together with the distribution of critical strains $D(\varepsilon_{ci})$ in the used bending beams can be represented by a lognormal distribution function:

$$D(\varepsilon_{ci}) \propto \exp \left( -\frac{1}{2} \left( \ln \varepsilon_{ci} - \ln \varepsilon_{m} \right)^2 \ln \gamma \right),$$

(2)

where $\varepsilon_{m}$ is the mean average value of the critical strains and $\gamma$ is their geometrical standard deviation. This assumption is more reasonable than a normal (Gauss) distribution function because the lognormal distribution function does not permit negative critical strains. Therefore, the whole crack induced
Table 1
Fit parameters of Eq. (3) fitted to the crack affected experimental results shown in Fig. 2 for various number of cycles to fatigue and heat treatments.

<table>
<thead>
<tr>
<th>Fatigue and heat treatment</th>
<th>Average critical strain, $\varepsilon_c (\times 10^{-6})$</th>
<th>Geometrical standard deviation, $\gamma$</th>
<th>Damping strength, $A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2190000</td>
<td>91</td>
<td>2.49</td>
<td>0.0236</td>
</tr>
<tr>
<td>+530 °C for 1 h</td>
<td>18</td>
<td>3.10</td>
<td>0.0097</td>
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<td>+50000</td>
<td>68</td>
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<td>0.0794</td>
</tr>
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<td>12</td>
<td>6.05</td>
<td>0.0111</td>
</tr>
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<td>+34 200</td>
<td>8.3</td>
<td>4.76</td>
<td>0.0666</td>
</tr>
<tr>
<td>+530 °C for 15 h</td>
<td>31</td>
<td>2.94</td>
<td>0.0828</td>
</tr>
<tr>
<td>+34000</td>
<td>0.6</td>
<td>2.46</td>
<td>0.0175</td>
</tr>
<tr>
<td>+530 °C for 25 h</td>
<td>17</td>
<td>2.64</td>
<td>0.0905</td>
</tr>
</tbody>
</table>

Damping is given by

$$\delta_c(\varepsilon) = A \int_{\varepsilon_0}^{\varepsilon_c} \left(\frac{\varepsilon_c}{\varepsilon}\right)^2 \exp\left(-\frac{1}{2} \left(\frac{\ln(\varepsilon_c - \ln(\varepsilon_m))}{\ln(\gamma)}\right)^2\right) \, d\varepsilon_c,$$

(3)

where $A$ is the damping strength taking into account the number of cracks and their specific contribution to damping. Some examples of resulting curves normalized to the respective maximum are given in Fig. 5 for various geometrical standard deviations. The smaller $\gamma$, the more similar is the curve to the elementary damping process, the greater $\gamma$, the more similar is the curve to the lognormal distribution function.

Fig. 2 shows the curves of Eq. (3) fitted to the experimental damping results affected by cracks. In Table 1, the corresponding fit parameters are summarised. The curves represent the measured values fairly well, except some small deviations that can be attributed to the more optional choice of the distribution function. Even the curves for the heat-treated sample fit the measured values not so bad although crack effects are smaller.

5. Conclusions

From the measured fatigue-affected Young’s modulus (Fig. 5), the damping curves and the damping model (Fig. 2, Table 1), the following conclusions can be drawn.

1. Increasing number of cycles to fatigue increases the maximum and shifts it to smaller strains. This is reasonable if one assumes that during cycling both, crack nucleation, and crack growth take place and that the critical strain of a crack is monotonously decreasing with crack length $l$, e.g. like a demand of crack growth theory:

$$\varepsilon_c \propto \frac{1}{\sqrt{l}}$$

(4)

This is found to be in contrast to the crack development of metallic foams during cycling where the crack length is limited by the thickness of cell walls [9].

2. Annealing at high temperatures decreases the maximum (smaller $A$), shifts it to lower strains (smaller $\varepsilon_m$) and levels it off (higher $\gamma$). This indicates that the damping contribution of small cracks and cracks with $\varepsilon_m$ in the vicinity of $\varepsilon_c$ is mainly affected by the heat treatment. This agrees with the fact that mainly the crack tips are changed by diffusion processes and suggests a serious influence of the crack tips in the damping process of cracks in AZ91, e.g. by emission of dislocations or by small crack growth.

3. The crack healing influence of annealing on damping is much higher than on Young’s modulus. This also suggests the dominant role of crack tips in the damping process in AZ91.

References