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Influence of heat treatment on damping behaviour of the magnesium wrought alloy AZ61

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Abstract

The effect of isochronal heat treatments for 1 h on variation of damping, hardness and microstructural change of the magnesium wrought alloy AZ61 was investigated. Damping and hardness behaviour could be attributed to the evolution of precipitation process. The influence of precipitation on damping behaviour was explained in the framework of the dislocation string model of Granato and Lücke.

Keywords: Magnesium; AZ61; Damping; Precipitation

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1. Introduction

Magnesium is the lightest of all metals used for constructional parts and therefore particularly attractive for automotive applications in the last two decades. Moreover, magnesium alloys take great importance to reduce vibration and noise in industrial machines. In order to substitute established materials like aluminium and steel components of magnesium alloys have to stand elevated temperatures. Thus, hot strength and creep resistance can be considered to be the most important properties of magnesium alloys to be optimized ^[1]. These properties are significantly dependent on the evolution of microstructural defects ^[2]. It is well known that damping is a sensitive indicator of microstructural changes caused by thermal treatment procedures ^[3].

Some magnesium alloys commonly used for structural applications are based on the magnesium-aluminium-zinc, such as AZ61 which has good mechanical properties at room temperature and is low-cost ^[4]. The aim of the present paper is to show the influence of different isochronal heat treatment on these properties in AZ61 magnesium alloys.

2. Experimental details

Heat treatment investigations were performed with the magnesium wrought alloy AZ61. The chemical composition of alloy is shown in Table 1.

Table 1

Chemical composition of the used magnesium sample (wt.%).

Alloy	Zn	Al	Si	Cu	Mn	Fe	Ni	Total Others
AZ61	0.99	6.5	0.002	<0.001	0.20	0.003	<0.001	<0.30

Specimens for damping measurements were machined to bending beams of 120 mm length, 2 mm thickness and 10 mm width. The cast specimens were isochronally annealed for 1 hour in a thermostated furnace and afterwards quenched in water at room temperature. The annealing temperature for AZ61 magnesium alloy was increased in steps of 50°C from room temperature up to 400°C.

Damping was measured at room temperature in terms of the logarithmic decrement of free decaying bending beam vibrations starting from maximum strain amplitude of about $\varepsilon = 1.0 \times 10^{-3}$. In order to get information about the influence of plastic deformation on the damping a lower maximum strain amplitude of $\varepsilon = 0.2 \times 10^{-3}$ was partially applied. The bending beam 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 mode (clamped free bar with end loading) by an alternating magnetic field. Resonant frequencies ranged from 36.7 to 37.2 Hz. The experimental setup is described in detail elsewhere ^[5].

The studies were accompanied by microstructural analyses using scanning electron microscope (ZEISS DSM 962) and hardness (HV 10) measurements.

3. Results and Discussion

In Fig. 1 the logarithmic decrement δ of the magnesium alloy AZ61 is plotted versus the maximum strain amplitude ε in logarithmic scale for different heat treatments ranging from room temperature up to 400°C. The heat treatment at room temperature means a measurement in the as cast condition of the sample. The curves can generally be divided into two parts, a strain independent part δ_0 at low strain and a strain dependent part δ_n at higher strain which increases with rising strain amplitude. Hence, the damping can be expressed by ^[6]:

$$\delta(\varepsilon) = \delta_0 + \delta_h(\varepsilon) \quad (1)$$

It is obvious that between room temperature and 150°C the strain dependent damping part is very similar but after a heat treatment of 200°C a decrease of the maximum damping is observable which is in addition shifted to higher maximum strain amplitude ε . After annealing at 250°C and 300°C a significant reduction of the strain dependent damping occurs. In contrast to the previous curves a damping peak is received. However, the shift of the maximum damping to higher ε continues. This progress is stopped after heat treatments at 350°C and 400°C. In these cases also a damping peak develops but its maximum arises at smaller strains than before and the strain dependent damping part is increased. For highest strain amplitudes the damping measurements show a monotonously increasing damping as obtained for the measurements after heat treatments from room temperature to 200°C.

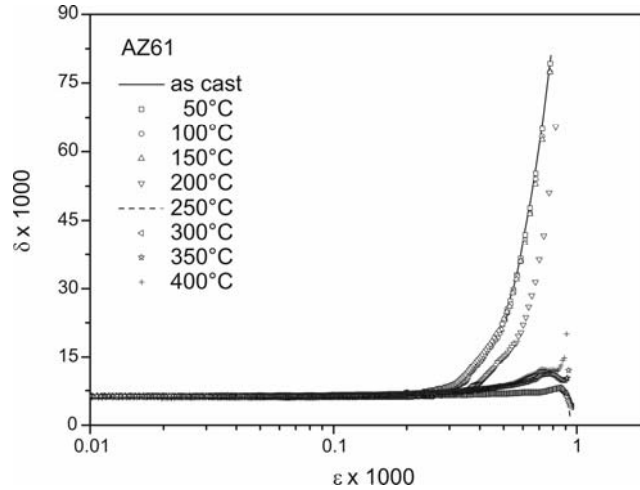


Fig 1. Development of strain dependent damping of AZ61 after stepwise increase of the annealing temperature.

In Fig. 2 the strain independent damping δ_0 is plotted versus the heat treatment temperature using two different starting maximum strain amplitudes of $\varepsilon = 0.2 \times 10^{-3}$ and $\varepsilon = 1.0 \times 10^{-3}$. In both cases δ_0 increases with rising temperature and shows a damping maximum at about 260°C. After passing that temperature δ_0 strongly

decreases. However, the results exhibit an influence of ε on δ_0 . The strain independent part is overlapped by another mechanism to be taken into account when using higher starting strain amplitudes. This mechanism is plastic deformation and was shown in a previous paper on fatigue-dependent damping [7].

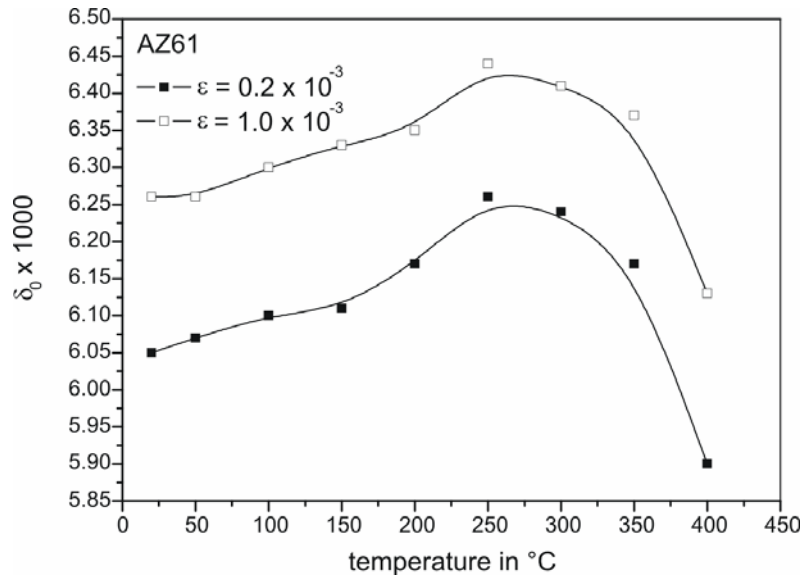


Fig. 2. Development of strain independent damping δ_0 at $\varepsilon = 0.2 \times 10^{-3}$ and $\varepsilon = 1.0 \times 10^{-3}$ versus the annealing temperature of AZ61.

When measuring the hardness as a function of the heat treatment temperature as illustrated in Fig. 3 it becomes evident that the curve shows a similar temperature dependency as seen in Fig. 2. In both cases changes of δ_0 and hardness, respectively, are more pronounced for temperature higher than 150°C . A hardness peak with a maximum around 250°C develops and a steep decrease of the hardness after passing the maximum occurs. Therefore, it can be assumed that the strain independent damping δ_0 and the hardness correlate with each other and are dependent on the same microstructural changes.

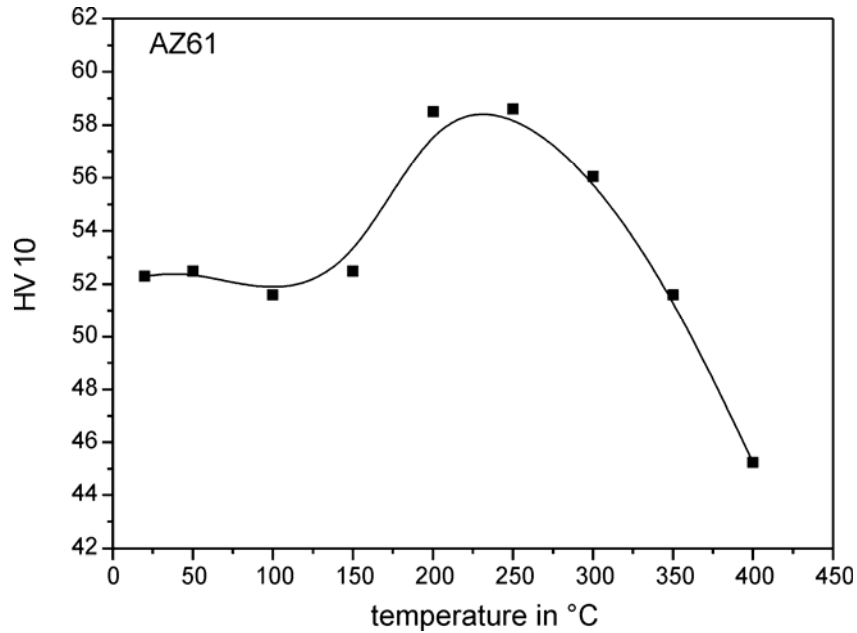


Fig. 3. Development of Vickers hardness of AZ61 with increasing annealing temperature.

Fig. 4 shows the SEM analyses of the magnesium alloy AZ61 after different heat treatments. In cast condition (Fig. 4, a) the microstructure consists of remaining eutectic which is stable up to about 400°C annealing temperature. After a heat treatment of 200°C (Fig. 4, c) the presence of a new phase near the eutectic zone is visible which is in accordance with the corresponding phase diagram of AZ61^[4] and is analysed as the intermetallic precipitating phase Mg₁₇Al₁₂ with lamellar structure^[8], dominating the mechanical properties of this alloy at elevated temperatures^[9]. The precipitation process in the Mg-Al-Zn-system appears to involve solely the formation of the equilibrium phase Mg₁₇Al₁₂^[10].

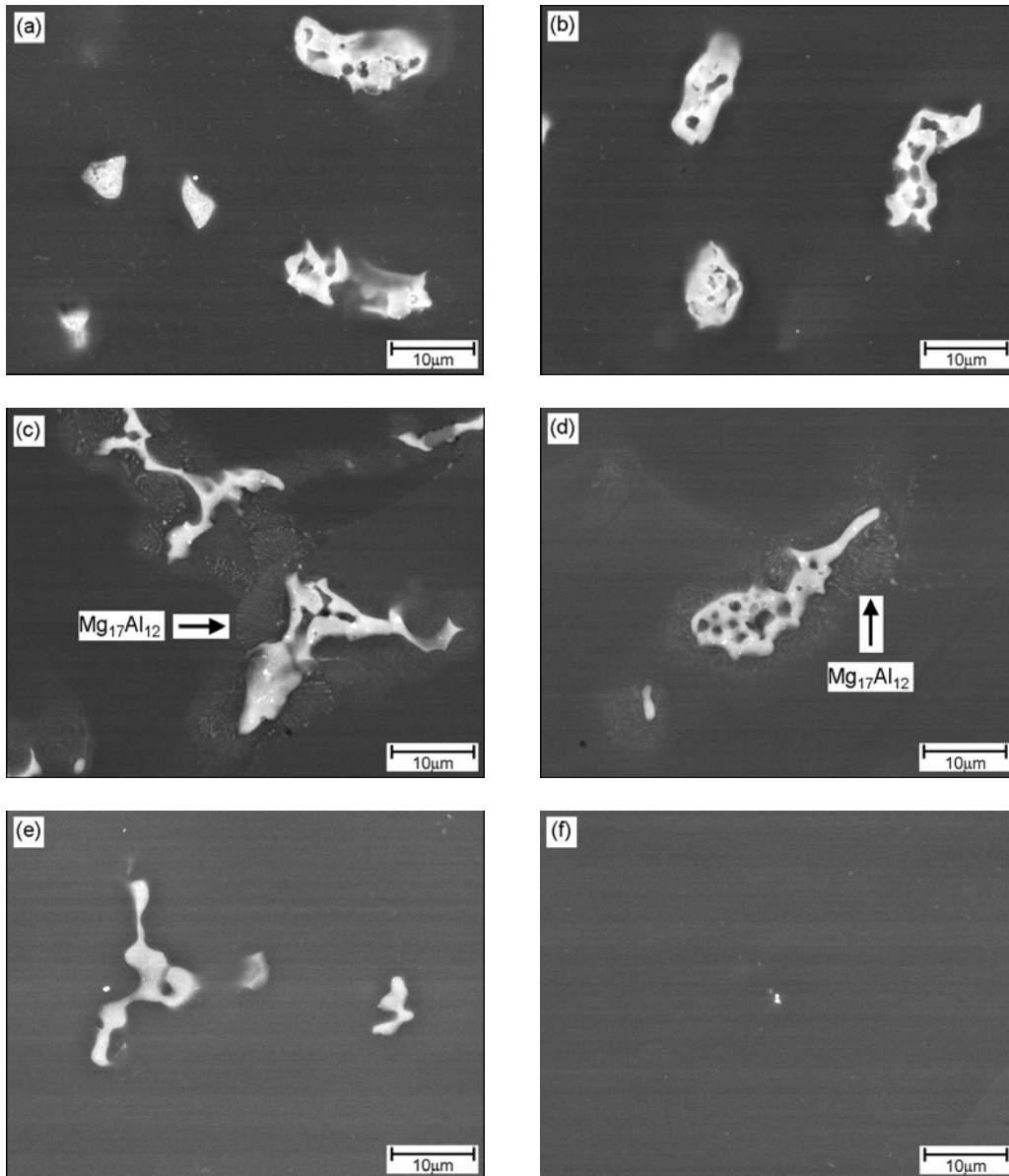


Fig. 4 Microstructure of specimens after following heat treatments: (a) room temperature (as-cast condition), (b) 100°C, (c) 200°C, (d) 250°C, (e) 350°C, (f) 400°C.

This phase is still present after annealing at 250°C (Fig. 4, d) and dissolved for the following heat treatments of 350°C (Fig. 4, e) and 400°C whereas at the final temperature of 400°C the matrix is almost free of remaining eutectic (Fig. 4, f). The less formation of precipitation was confirmed by electrical resistivity measurements of the

magnesium alloy AZ91 indicating a strong activation of precipitation around 230°C followed by a decreased influence of the temperature and a regression of precipitates [11, 12].

As mentioned damping (Fig. 2) and hardness (Fig. 3) are correlating and due to the SEM analyses hardness increases by precipitation hardening. An increase in strength which interacts with hardness was also reported by Lagowski [13] attributed to the decrease in interprecipitate spacing. Hence, damping is as well dependent on this mechanism. The maximum of hardness and damping can be assigned to intensified formation of precipitates.

According to the theory of Granato and Lüke [14] the value of the strain independent logarithmic decrement δ_0 is proportional to the product of the dislocation density and the fourth power of the average distance between weak pinning points on dislocations, i.e.

$$\delta_0 \approx \rho l^4 \quad (2)$$

where ρ is the dislocation density and l^4 the average dislocation distance between weak pinning points, respectively. Granato and Lüke developed a model describing the interaction of dislocations with pinning points (GL-model, [14]). In this model a dislocation segment is anchored by two kinds of pinning points that restricts the dislocation motion. It is assumed the mean distance L of the dislocation is fixed at strong pinning points (e.g. matrix atoms). For small oscillation stress (resulting material strain $\varepsilon \approx \sigma/E$; σ : applied stress, E : Young's modulus) the dislocation bows out between the weak pinners (e.g. foreign atoms) with mean distance l . This dislocation motion characterizes the strain independent damping δ_0 . When the stress amplitude of the alternating vibration becomes larger than a critical stress the dislocation segment will break away from all other weak pinners contained within L , leading to a drastic

instantaneous increase in dislocation damping (Fig. 5). The strain dependent damping δ_h is characterized by this irreversible dislocation motion.

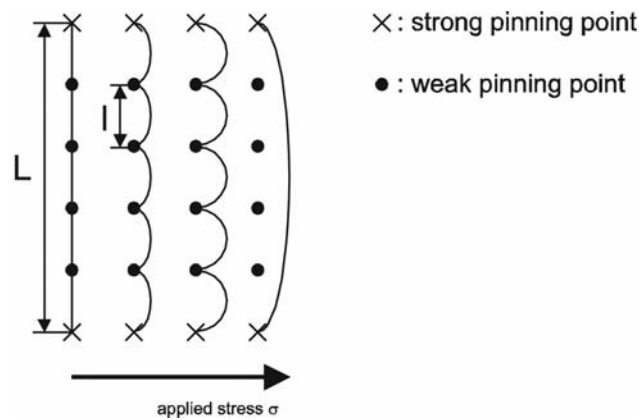


Fig. 5. Dislocation string model of Granato and Lücker^[14] illustrating the bowing out and breakaway by an increasing applied stress σ .

Precipitates can act as obstacles^[3] and their fraction is dependent on the temperature. In the framework of this model and considering Eq. (2) an increase in δ_0 after heat treatments between 150°C and around 250°C is due to an impoverishment of foreign atoms in the matrix. The mean distance l between weak pinning points becomes larger and the dislocation segments can bow out easier. When occurs the dissolution of the intermetallic phase, δ_0 should behave contrarily as such is experimentally observed.

The influence on the strain dependent damping δ_h is still debatable. As shown in Fig. 1 δ_h is reduced after a heat treatment of 200°C. Zhang et al.^[15] determined that if precipitation takes place, precipitates of $Mg_{17}Al_{12}$ form new strong pinning points. This corresponds to a decrease of the mean distance L causing a decrease of the strain dependent damping. The curves presented in Fig. 1 show that two mechanisms of increase of damping exist. The first mechanism was already discussed and interpreted as a mechanical unpinning of dislocation segments. It results in an approximately exponential curve (δ_h). But the measurements show also a “hump” at higher strains which does not correspond to the main characteristic of δ_h . This additional damping is

related to plastic strain (see Fig. 6) and called δ_p [16]. It implicates an increase in dislocation density and should lead to a shift of the maximum damping to higher strain amplitudes which is obtained. The influence of the plastic strain on the strain independent damping δ_0 is illustrated in Fig. 2. Comparing the temperature dependency of δ_0 using two different starting maximum strain amplitudes it becomes evident that δ_0 is overlapped by the plastic damping. From these results Eq. (1) can be rewritten as

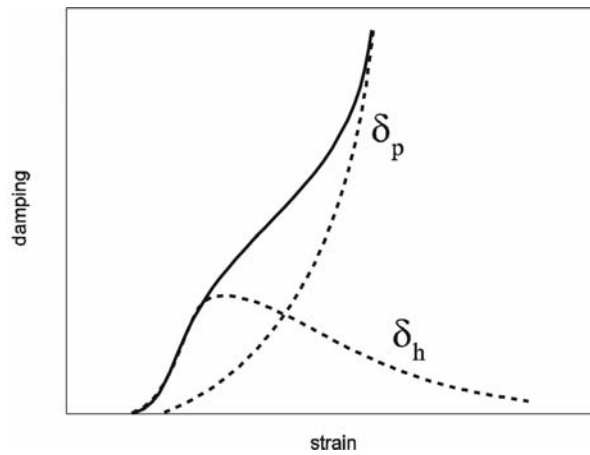
$$\delta(\varepsilon) = \delta_0 + \delta_p + \delta_h(\varepsilon). \quad (3)$$


Fig. 6. Resulting damping as the combination of the two types of internal friction, δ_h and δ_p .

4. Conclusions

Based on these investigations it can be stated that both hardening and damping depend on the precipitation development during heat treatment. The strain independent damping δ_0 and hardness of the isochronally heat treated magnesium alloy AZ61 increase considerably with the formation of precipitated $Mg_{17}Al_{12}$. The strain dependent damping δ_h is dependent on the amount of precipitates, too. But with rising fraction of precipitates a decrease of δ_h is measured. Both observations can be well described within the framework of the dislocation string model of Granato and Lücke. In case of

plastic deformation the damping curve can change leading to a peak at higher maximum strain amplitudes and/or a general increase of the total damping.

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