GRAIN SIZE EFFECT ON STRAIN HARDENING AND ACOUSTIC EMISSION OF MAGNESIUM ALLOY AS21X

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The effect of grain size on strain hardening of magnesium alloy AS21X was investigated by room temperature tensile tests with concurrent *in-situ* acoustic emission (AE) measurements. Material was prepared by high-pressure die-casting and direct squeeze--casting resulting in two different microstructures, fine and coarse grained ones, respectively. The strain hardening rate was determined, along with the AE count rate, as a function of stress and strain. The different microstructures showed distinct strain hardening behaviour. The coarse grained material exhibited a tensile curve with parabolic shape, whereas the fine grained material had a marked yield plateau.

K e y w o r d s: magnesium alloys, plastic deformation, acoustic methods, tension test

VLIV VELIKOSTI ZRNA NA DEFORMAČNÍ ZPEVNĚNÍ A AKUSTICKOU EMISI HOŘČÍKOVÉ SLITINY AS21X

V práci jsme studovali vliv velikosti zrna na deformační zpevnění hořčíkové slitiny AS21X podrobené tahovým zkouškám za pokojové teploty. Současně byla registrována odezva akustické emise (AE). Materiál byl připraven jednak vstřikovým litím, které vedlo k jemnozrnné struktuře, a dále tlakovým odléváním (squeeze-casting), vedoucím k hrubozrnné struktuře. Materiál s hrubším zrnem ukazuje nízkou mez kluzu a parabolické zpevnění, jemnozrnný materiál se vyznačuje výrazně vyšší mezí kluzu a platem na mezi kluzu. Byla nalezena výrazná korelace mezi deformačními křivkami, resp. mezi rychlostí deformačního zpevnění a parametry akustické emise.

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1. Introduction

Magnesium alloys, as the lightest structural materials, are very attractive in many applications as they exhibit a high specific strength (yield stress to density ratio), a superior damping capacity and a high thermal conductivity. However, they possess a low cold formability and a low creep resistance.

In order to improve the ductility of Mg alloys, it is important to understand their deformation behaviour. The mechanical properties of Mg alloys are governed by the mechanisms of plastic deformation characteristic of hexagonal close-packed (hcp) metals. Specifically, in violation of the von Mises criterion for compatibility of plastic deformation of polycrystals (requiring at least five independent slip systems), hcp metals possess only three independent primary slip systems, associated with the basal planes (0001). Furthermore, Mg exhibits an axial ratio c/a equal to 1.623, which is slightly less than the ideal value of 1.633. Consequently, dislocation glide in Mg is accompanied by twinning, which takes place on the pyramidal planes $\{10\bar{1}1\}$ [1]. Twinning may also reorient the basal planes in particular grains so that they become more favourably oriented for basal slip [2].

Acoustic emission (AE) is an experimental technique, sensitive to transient elastic waves generated within a material due to sudden structural changes. It has been established that AE is a viable procedure for monitoring the development of microstructural changes and related plastic deformation in many classes of materials. In particular, generation and collective motion of dislocations are generally recognized to produce significant AE in most metals and alloys [3]. Hence, AE monitoring can be used to identify and characterize the deformation mechanisms occurring in Mg alloys and to correlate them with the associated mechanical behaviour.

To date, results on the AE response of deformed Mg alloys are fairly scarce [4–7]. These have shown distinct correlations between the AE activity and the sample orientation, purity, strain rate, and the mode of testing (tension or compression). In all cases, deformation twinning and dislocation glide were found to be major sources of AE.

Recently, several papers correlating deformation mechanisms and AE parameters for Mg alloys with various fabrication histories and for different testing conditions were published. The influence of the rolling direction [8, 9], the fabrication technique [10] and the mode of testing [11] were studied. The present paper continues the mentioned series by reporting results on monotonic tensile tests of magnesium alloy AS21X with different microstructures and the attendant AE.

2. Experimental

Fine grained magnesium alloy AS21X (Mg-2.2Al-1.0Si-0.08Mn-0.12MM in wt.%) specimens were produced by high pressure die-casting. The specimens were prepared in accordance with ASTM standard B 557M-94 for tension testing of die-cast magnesium alloy products [12]. The specimen diameter was 6.0 mm and the gauge length was 75 mm. Material with the same chemical composition was also squeeze-cast into discs with diameter of 200 mm and height of 45 mm to produce a coarse microstructure. Round specimens for tensile testing, with gauge length of 25.4 mm and diameter of 4.5 mm were machined from bulk material in the as-cast state. The microstructures were investigated by light optical microscopy with digital picture analysis. Sections for metallography were prepared using standard grinding and polishing procedures. The etchant used was acetic-picral [13]. The average grain size was determined by the planimetric method [14]. The specimens were pulled to fracture in a universal testing machine at constant cross-head speed corresponding to an initial strain-rate of $10^{-3}\cdot s^{-1}$. A computer controlled DAKEL-XEDO-3 AE system was used to perform monitoring (two-threshold-level detection, total gain of 94 dB) and full analysis of AE. Full information on the XEDO system may be found on the web [15]. An LB 10A standard AE transducer (almost flat response in a frequency band from 100 to 600 kHz) was attached to the specimen surface with the help of grease and a spring.

3. Results

The direct squeeze-casting method produced a coarse dendritic microstructure with characteristic 'Chinese script' Mg_2Si precipitates (Fig. 1). The average dendrite size was 370 μm. High-pressure die-casting lead to a fine grained microstructure (Fig. 2) with an average grain size of 10 μm.

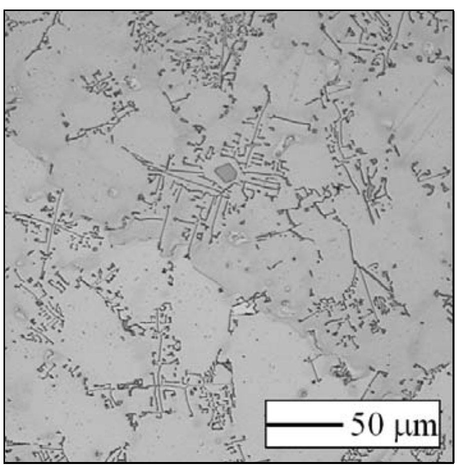

Fig. 1. Microstructure of the squeeze-cast AS21X alloy.

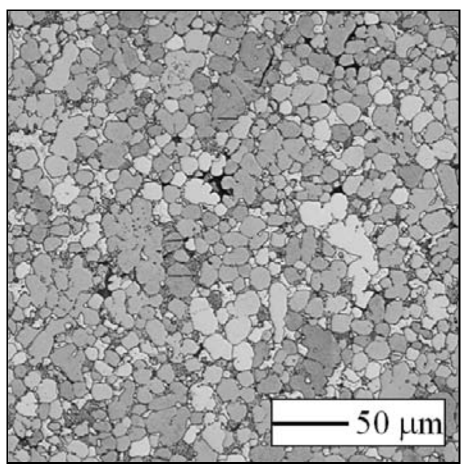

Fig. 2. Microstructure of the high-pressure die-cast AS21X alloy.

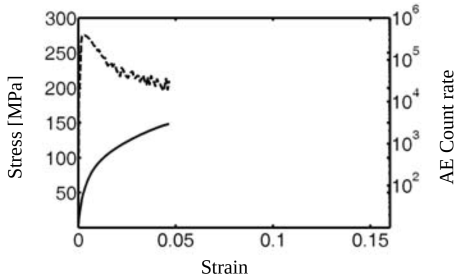

Fig. 3. Typical true stress vs. true strain (—) and AE (– – –) curves for squeeze-cast AS21X.

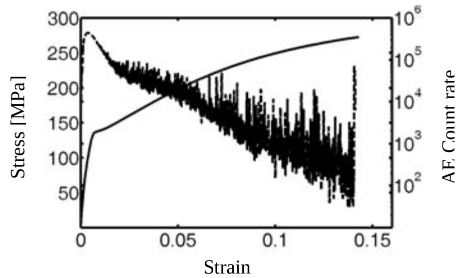

Fig. 4. Characteristic true stress vs. true strain curve (—) and AE (– – –) for high-pressure die-cast AS21X.

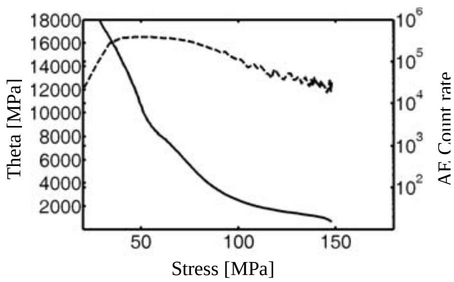

Fig. 5. Strain hardening rate vs. stress (—) and AE (– – –) for squeeze-cast AS21X.

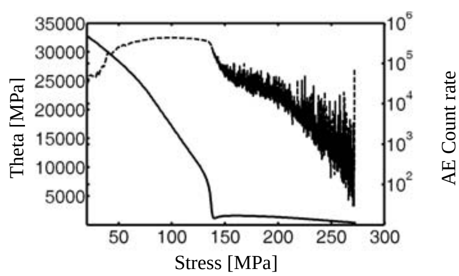

Fig. 6. Strain hardening rate vs. stress (—) and AE (– – –) for high-pressure die-cast AS21X.

The difference in microstructure is reflected in the tensile properties. The tensile curve for the squeeze-cast material has a parabolic shape without any macro--elastic part and any distinct yield point as depicted in Fig. 3. By contrast, the high pressure die-cast material displayed an apparent yield plateau, as illustrated in Fig. 4. Also, the high pressure die-cast material exhibits a higher strength and enhanced ductility in comparison to the squeeze-cast one. The stress vs. strain curves correspond with the strain dependences of the AE count rates and the r.m.s. voltage. There is always a characteristic peak in the count rate close to the yield point, followed by a decrease in the AE activity with further straining. This situation is also depicted in Figs. 3 and 4 for the count rate at the lower threshold level.

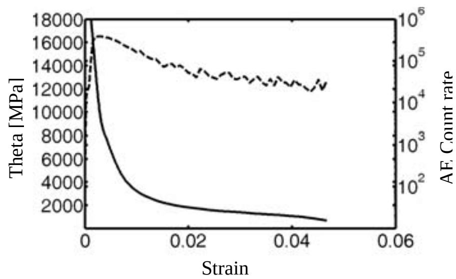

Fig. 7. Strain hardening rate vs. strain (—) and AE (– – –) for squeeze-cast AS21X.

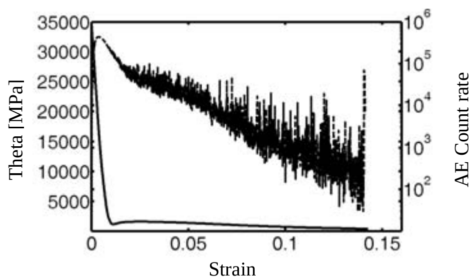

Fig. 8. Strain hardening rate vs. strain (—) and AE (– – –) for high-pressure die-cast AS21X.

In order to reveal a direct correlation between strain hardening and the AE response, the strain hardening rate and the AE count rate are plotted vs. stress (Figs. 5, 6) and vs. strain (Figs. 7, 8). For the squeeze-cast material the AE peak occurs at a stress of 40 MPa and corresponds to a change in slope in the strain hardening curve, as seen in Fig. 5. The AE count rate and the strain hardening rate (theta) then decrease rapidly with increasing stress.

For the high pressure die-cast material, the yield plateau leads to a hardening curve with a distinctive 'dip'. The maximum AE count rate is found preceding the yield plateau at a much higher stress of 100 MPa. Subsequently, the AE count rate decreases with increasing stress; this decrease becomes more significant when the strain hardening rate approaches zero (i.e. dislocation structure evolution approaches a steady state). Similar correlations are seen in plots of Figs. 7 and 8. It is noteworthy that AE signals appear throughout the whole test, in contrast with, e.g., aluminium and aluminium alloys (cf. [3, 16]).

4. Discussion

The coarse microstructure of the squeeze-cast alloy is caused by the low solidification rates obtained when casting thick sections. This exemplifies the section thickness limitations on casting magnesium into structural parts. An early beginning of a significant AE activity, i.e. no pronounced acoustic yield point, well corresponds to the absence of any macro-elastic deformation. Such behaviour was already reported in [11]. A pronounced AE, achieving rapidly a peak at a low stress of 40 MPa, is believed to be due to intense twinning and dislocation multiplication, in agreement with the findings of Bell and Cahn [17], who showed that there is no critical resolved shear stress for twinning. Twins nucleate owing to high local stresses in front of large dislocation pile-ups, which may form in large grains. Large twins or twin intersections as possible nuclei of cracks are also likely a reason for early fracture in this alloy, in accordance with [18]. It should be noted that a significant decrease in ductility with increasing grain size was also observed in Zn (exhibiting similar deformation mechanisms) [19].

An improved strength in the pressure die-cast alloy can be accounted for by a fine grain structure. A much higher applied stress is needed to activate dislocation multiplication and to nucleate deformation twins. Once the yield stress of the material is achieved, an intense plastic deformation by dislocation multiplication and twinning occurs at random locations within the specimen and propagates to the virgin sample volume, thereby leading to a pronounced yield plateau. This stage is followed by a short stage of further strain hardening and subsequent saturation of the dislocation structure, which results in a gradual decrease in the AE activity. A more rapid drop-off is recorded when the dislocation structure tends to steady state (cf. the breakpoints in Figs. 6, 8). However, as distinct from aluminium and its alloys, AE in alloy AS21X does not vanish completely, which indicates persisting twinning activity, secondary dislocation motion in re-oriented grain parts throughout the whole tests, and activity of non-basal slip systems [20, 21]. The essential mechanisms of plastic deformation (twinning and dislocation motion) are probably the same in both materials irrespective of the grain size, as the corresponding parts of the AE plots (Figs. 3–8) are nearly identical. However, the twins should differ in size, which could influence the distributions of AE signals. In interpreting the data in terms of the grain size effect, the dislocation motion on non-basal slip systems should also be considered. This analysis will be the object of further investigations.

5. Conclusions

The AS21X alloy produced by the direct squeeze-casting method has a coarse dendritic microstructure with characteristic 'Chinese script' precipitates and an average dendrite size of 370 μm. The squeeze-cast material exhibits poor strength and tensile ductility. The AE response was detected at very low stresses and no pronounced acoustic yield point was found. An intense AE activity persists until fracture of the material.

High-pressure die-casting leads to a fine grained microstructure with an average grain size of 10 μm. A pronounced yield plateau, enhanced strength and improved ductility in comparison with the squeeze-cast material were found. An intense AE response precedes the yield plateau and also persists until fracture, well correlated with the evolution of the strain hardening rate.

An interplay of dislocation motion and deformation twinning (including dislocation slip in twinned volumes) is typical for deformation behaviour of both materials.

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