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The skin effect and the yielding behavior of cold chamber high pressure die cast Mg–Al alloys

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ABSTRACT

The volume fraction of material that remained elastic as yielding developed in cast-to-shape tensile specimens of binary alloys with Al contents between 0.47 and 11.6 mass% was calculated using the Kocks–Mecking method of analysis. In the most dilute alloys the elastic fraction decreased rapidly to zero at a well-defined stress, suggesting that yielding was uniform across the specimen, whereas in the concentrated ones it decreased gradually over a wide range of stresses, suggesting that yielding developed first in the softer core of the casting while the harder outer layer, or skin, remained elastic. Comparison with specimens of the concentrated alloys which had a surface layer removed showed that the strain hardening behavior of the core resembled that of full specimens of the most dilute alloy. The maximum amount of elastic material in comparison with the most dilute alloy was used to define the area fraction covered by the skin, for each alloy. The skin covered between ~10% and ~30% of the cross section, the greater values for the concentrated alloys. The skin imposed an elastic constraint that delayed the development of full plasticity at the core.

1. Introduction

The fast cooling rate inherent in the high pressure die casting (hpdc) process generally refines the grain and eutectic microstructures of Mg–Al alloys, but also creates gradients of scale and composition across the casting thickness [1–4]. When the castings are made in a cold chamber press, a bimodal grain microstructure consisting of a mixture of fine (4–10 μm [5–7]) α (Mg) grains solidified inside the die cavity and large (10–50 μm [5,6,8]) externally solidified grains (ESGs) formed due to incipient solidification in the shot sleeve, is normally observed over the casting cross section [4,9–11], adding to the inhomogeneity of the microstructure. Near the surface [6,10] the fine α (Mg) grains predominate, forming what is called the casting “skin”, whereas the ESGs predominate at the center of the cross section, or “core”. Pronounced coring results in non-equilibrium eutectic surrounding the fine α (Mg) grains, even in dilute alloys [2,4,6,12]. At the core the accumulation of ESGs results in a lower volume fraction of eutectic and reduced degree of spatial interconnection of the intermetallics in comparison with the skin [2,3,12–15]. A detailed statistical analysis of the grain size distributions at the skin and core regions of the alloys of this study can be found elsewhere [6] whereas the 3D morphology and degree of interconnection of the eutectic phases of a related Mg–Al alloy (AZ91) was characterized by 3D-FIB tomography in Ref. [15].

The effect of solute content and casting geometry on the yield strength and the ductility of hpdc Mg–Al alloys has been characterized in detail in the literature [3,12,16–18], but with scant quantitative data on the effect of solute on the relative strengths of skin and core. Microhardness testing in the concentrated alloys of this study showed that the skin may be up to 30 HV [19] harder than the core whereas in alloy AM60B the skin was reported to be 25% harder than the core [14]. The difference in hardness between skin and core stems from the disparity in the respective Hall–Petch, solid solution and dispersion hardening [7,12,14,19–22].

Being softer, the core is likely to deform first, and this is implicitly or explicitly accepted in the literature [1,9,12,14,20–22], but systematic studies on how yielding develops across the cross section of the casting are lacking. Likewise, the fraction of the cross section occupied by the skin has been estimated using metallographic or geometrical arguments [4,23–25], through experiments involving hardness profiles [9,22,25], microhardness mapping [19–21], by removing successive surface layers [9,26] prior to tensile testing, and by finite element modeling [1,22], but no direct quantitative determinations of this fraction and how it affects the yielding behavior have been published. Non-uniform yielding may affect the component’s behavior during service, especially regarding fatigue or creep. Thus, understanding how yielding develops

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Table 1
The concentration of Al in the alloys studied, measured using atomic emission spectroscopy (ICP-AES).

Alloy	1	2	3	4	5	6	7
Al (mass%)	0.47	0.93	1.82	4.37	5.51	8.77	11.6

across the casting cross section is essential for both alloy selection and component design.

When a fraction of the cross section of a deforming metal remains elastic, the slope of the stress–strain curve is greater in comparison with that of the fully plastic material, as described using continuum mechanics arguments by Masing [27] and for dispersion hardened alloys by Brown and co-workers [28–30]. The determination of the strain hardening rate during yielding should enable, in principle, apportioning the elastic and plastic components of the cross section for each alloy. A proven tool for this sort of analysis is the method developed by Kocks and Mecking [31].

In this work the strain hardening behavior at low strains of seven hpdc binary Mg–Al alloys was analyzed using the Kocks–Mecking approach. The compositions studied, 0.47–11.6 mass% Al, were selected in order to produce microstructures with increasing differentiation between the skin and core, as described in prior work on the same alloys [6,19,32]. The ultimate goal of the analysis was the determination, for given alloy and applied stress, of the fraction of cross section (the skin) that remained elastic as the specimen progressively yielded.

2. Materials and experimental methods

Table 1 shows the Al content of the alloys studied. Tensile specimens of rectangular cross-section (5.75 mm width and 3 mm thickness, gauge length 30 mm) with dog-bone shape were cast-to-shape using a 250 T cold chamber high pressure die cast press. The casting parameters can be found elsewhere [6]. In order to better identify the respective contribution of the skin and core to the total strength of the two most concentrated alloys, 500 μm were machined away from each of the wide-edge surfaces of several specimens (i.e., after machining, the specimens' final thickness was reduced from 3 to 2 mm; the width remained unchanged). All specimens were tensile tested on a hard-beam screw-driven machine fitted with hydraulic grips, at a crosshead speed of 1 mm/min, with a 25 mm knife-edge extensometer attached.

Samples for microstructural analysis were cut from the gauge length of undeformed specimens. Metallographic polishing was carried out down to 0.05 μm colloidal silica by standard methods. The polished sections were etched with ethylene glycol for observation at selected locations (see Fig. 1) using a scanning electron microscope (SEM).

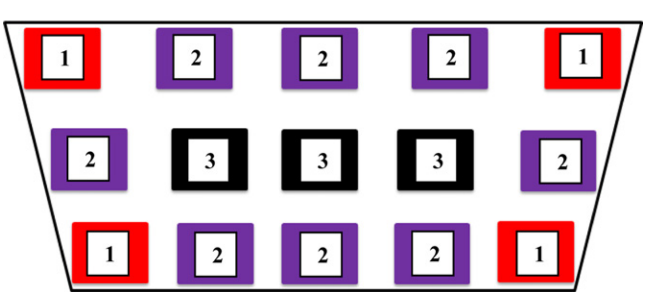

Fig. 1. Points identifying the skin, (corners (1) and surface (2)), and core (3) regions for SEM observation on the cross-section of tensile specimens.

3. Results

3.1. Microstructure

Three representative alloys from Table 1 are shown in Fig. 2. The microstructure of the most dilute alloy (0.47 mass% Al), Fig. 2a, consisted of grain boundaries and twins. The grain size (determined by EBSD in Ref. [6] on the samples of this study) was uniform across the cross section, with an average of ~14 μm. For the two concentrated alloys (4.37 mass% Al, Fig. 2b and 8.77 mass% Al, Fig. 2c), the primary α-Mg phase appeared dark, the eutectic α-Mg appeared grey and the β-$Mg_{17}Al_{12}$ intermetallic phase appeared bright. In both alloys the skin and core regions were equally well differentiated, with a prevalence of fine grains (6–9 μm in size) at the skin and large ESGs (10–20 μm in size) at the core [6]. Quantitative metallography on a related alloy (AZ91) published elsewhere [15] showed that the volume fraction of intermetallic was greater at the corners (~11.2%) and along the surfaces than at the core (~6.5%). Microstructural and mechanical parameters relevant to the alloys of this study are listed in Table 2.

3.2. Tensile behavior

The stress–strain curves of the alloys of Table 1 are compared in Fig. 3a. Fig. 3b makes more evident the differences in the flow behavior at very low strains (note that true plastic strain was used for the *x*-axis of Fig. 3b). The yield strength, *YS*, (see Row #5 in Table 2) was measured at a very low off-set strain of 0.05% (the intersection with the vertical line in Fig. 3b) instead of the usual 0.2% for reasons given later. The flow curves of the dilute (0.47, 0.93 and 1.82 mass% Al) alloys showed a high strain hardening rate in the first ~0.3% plastic strain, (the microplasticity region), followed by an inflection or incipient plateau and an extended linear hardening region once plastic deformation settled-in fully at ~1% strain. Macroscopic yielding developed at a fairly well-defined applied stress in the leaner alloys.

For the higher Al content alloys the strain hardening rate in the microplasticity region was considerably higher than for the dilute ones, and the incipient plateau was not present. The flow curves became increasingly rounder and yielding developed more gradually with increased solute. The specimens whose skin layer was removed (labeled NS in Fig. 3) generally reproduced the behavior of the full specimens, albeit with lower yield strength and a reduced slope in the microplasticity region (the latter is more evident in Fig. 3b).

4. Discussion

4.1. Yield and strain hardening behavior

Polycrystals of magnesium and its alloys, prior to the onset of full plasticity, exhibit an extended microplasticity region in which grains favorably orientated with respect to the tensile axis deform by basal slip whereas hard-orientated grains either remain elastic or twin [33–35]. Once the polycrystal becomes fully plastic by extensive activation of prism slip [33], the strain hardening rate drops to ~1.4 GPa, a value consistent with athermal accumulation of dislocations [36–38]. Concurrent activation of {10–12} twinning [39–41] creates an incipient plateau at low strains as those shown by the leaner alloys of Fig. 3. Although all of the flow curves of Fig. 3 generally conform to the above description, the more concentrated alloys exhibit two particular features relevant to this work: an increased slope during the microplasticity regime, and a rounded flow curve at yield in comparison with the more dilute alloys.

A rounded deformation curve is an indication of gradual (inhomogeneous) yielding, a behavior consistent with that of a