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Predicting the flow stress of high pressure die cast magnesium alloys

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ABSTRACT

In the present study, we describe the characterization of three magnesium alloys, AM60, AZ91 and AE44, which were processed by high pressure die casting (HPDC) and gravity casting. Spherical microindentation was used to analyze the influence of microstructural features on the flow stress for both skin (finer grain sizes) and core (larger grain sizes and dendrites) regions of HPDC, as well as different regions of gravity step-cast plate for all three magnesium alloys. It was observed that the local yield stress and flow stress of magnesium alloys depend on grain size. The Hall–Petch slopes determined from indentation testing compared well with the results obtained from uniaxial tensile testing and literature. The Hall–Petch equation was shown to be applicable for predicting the yield strength and the flow stress at several levels of plastic strains.

1. Introduction

Magnesium is the lightest of the engineering metals and therefore has application in the transportation industry for mass reduction. Magnesium automotive parts are primarily produced by high pressure die-casting (HPDC). The structural applications are currently limited by mechanical properties, particularly ductility, caused by local variation in microstructure [1,2]. A major research aim in cast magnesium alloys has been to predict the dependency of the mechanical properties on microstructural features such as grain size and porosity [3–5].

The base microstructure of HPDC magnesium alloy is typically comprised of fine grains near the walls, called the skin region and coarse grains in the center, referred to as the core region [1,2,6]. In the case of HPDC, ductility strongly depends on porosity and grain size and, to a lesser extent, the skin thickness. Ductility is an indirect measure of energy absorbed during impact loading and higher ductility results in better energy absorption [7]. Since the grain size is controlled by the cooling rate, a variation in solidification conditions leads a wide range of grain sizes. As opposed to the HPDC process, the relatively slow cooling rates encountered in the gravity sand casting process tend to produce coarse microstructures which may lead to lower ductility.

Standard uniaxial tensile testing is typically used to analyze the mechanical properties of magnesium alloys such as yield strength, strain hardening coefficient and Young's modulus. The influence of local mechanical properties of the skin and core regions on the overall mechanical response can not be characterized using conventional test methods performed on the macro-scale. The micro or nanoscale indentation technique is very well suited for characterization of the mechanical properties of localized regions. In the present study, spherical microindentation is used to characterize the local properties of magnesium casting alloys, which were fabricated by HPDC and gravity step-casting. The dependency of local yield and flow stresses upon the variation of grain size is to be studied based on optical observation, mechanical testing as well as Hall–Petch predictions.

2. Background

2.1. Hall–Petch equation

The yield strength and flow stress of magnesium alloys are affected by the microstructural features [3,8]. Yield strength shows a direct dependency on the grain size as indicated in the Hall–Petch equation [9,10]:

$$\boldsymbol{\sigma}_y = \boldsymbol{\sigma}_0 + \boldsymbol{k}\boldsymbol{d}^{-1/2} \tag{1}$$

where $\boldsymbol{k}$, is the Hall–Petch slope, $\boldsymbol{d}$, is the average grain size, and $\boldsymbol{\sigma}_0$, is the intercept stress. A relationship between flow stress and grain size is also proposed [9]:

$$\boldsymbol{\sigma}(\boldsymbol{\varepsilon}) = \boldsymbol{\sigma}_0(\boldsymbol{\varepsilon}) + \boldsymbol{k}(\boldsymbol{\varepsilon})\boldsymbol{d}^{-1/2} \tag{2}$$

where $\boldsymbol{\sigma}(\boldsymbol{\varepsilon})$ is the flow stress at a given strain. Two main models have been proposed to justify the Hall–Petch equation, the

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dislocation pile-up model [11] and the work hardening (dislocation density) model [12,13]. According to the pile-up dislocation model, the Hall–Petch slope is theoretically constant, whereas the work hardening model predicts dependence of the Hall–Petch slope, $\boldsymbol{k}(\boldsymbol{\varepsilon})$, on plastic strain. It is implied that grain size has a strong contribution to increasing work hardening due to the additional limitation on dislocation motion caused by grain boundaries. The work hardening model was developed by Ashby [14] and considers that this dislocation density is necessary to accommodate the strain incompatibility in small grains with different crystallographic orientation. The modified model also predicts the strain-dependence of the Hall–Petch slope $\boldsymbol{k}(\boldsymbol{\varepsilon})$. In previous experiments, the Hall–Petch slope, decreases with increasing plastic strain which is not consistent with the expectation of the work hardening model [4,12].

2.2. Spherical indentation

The spherical microindentation technique was used to measure local flow stress for each specimen. The flow stress was obtained from indentation depth and load curve, using indentation theory developed by Tabor [15], Johnson [16] and Mesarovic and Fleck [17].

The average indentation stress, $\boldsymbol{\sigma_{avg}}$, is correlated to the mean contact pressure underneath the spherical indenter, $\boldsymbol{P_M}$, which is the ratio between the indentation load, and the projected indentation area. $\boldsymbol{\psi}$ is the constraint factor which depends upon the work hardening properties of the material and the shape of the indenter [16].

$$\boldsymbol{\sigma_{avg}} = \frac{\boldsymbol{P_M}}{\boldsymbol{\psi}} \tag{3}$$

It is proposed that the effects of work-hardening can be accounted for using a plasticity factor, $\boldsymbol{\Phi}$ which is determined by the mode of material response depended upon yield stress, $\boldsymbol{\sigma_y}$, modified Young's modulus, $\boldsymbol{E}^*(\boldsymbol{E}^* = \boldsymbol{E}/(1-\boldsymbol{v}^2))$,$\boldsymbol{v}$ is Poisson's ratio), and the ratio of the contact radius to the radius of spherical indenter ($\boldsymbol{a/R}$).

$$\Phi = \frac{\boldsymbol{a}}{\boldsymbol{R}}\frac{\boldsymbol{E}^*}{\boldsymbol{\sigma_y}} \tag{4}$$

There are three typical regimes of material deformation during spherical indentation: elastic deformation, elastic–plastic deformation and fully plastic deformation. The following equation presents the relationship between the constraint factor and plasticity parameter for the three regimes mentioned during spherical indentation testing [17].

$$\begin{aligned} &\boldsymbol{\psi} = \mathbf{1.3}, \quad \Phi < 2, \text{Elastic} \\ &\boldsymbol{\psi} = \mathbf{1.3} + \mathbf{0.0037}\Phi, \quad 2 < \Phi < 100, \quad \text{Elastic–plastic} \\ &\boldsymbol{\psi} = \mathbf{1.65}, \quad \Phi > 100, \quad \text{Plastic} \end{aligned} \tag{5}$$

3. Experimental method

3.1. Alloys and casting

The alloys examined in this work are AM60, AZ91 and AE44 which were processed by gravity step casting and HPDC. The nominal chemical compositions of those alloys are given in Table 1.

The step-shape plate castings were cast at CANMET – Materials Technology Laboratory in Ottawa, Canada, using a sand mold designed to promote directional solidification. A simplified step-shape plate casting geometry was designed with 330 mm in length, 100 mm in width, and thicknesses of increasing steps, ranging from 4 mm to 40 mm from the feeding riser. Six samples were selected from the various three regions of step-plates for three different magnesium alloys, as shown in Fig. 1. The HPDC plates were provided by Meridian Lightweight Technologies Inc. and measured 165 mm in length, 100 mm in width, and 3 mm in thickness.

3.2. Metallography

The grain structure was revealed by selectively etching in 1% Nital, 10% HF and Glycol for AM60, AZ91 and AE44 magnesium alloys, respectively. Digital image analysis was employed to measure grain size and area fraction of β-phase. The average grain sizes were determined by taking an average for five individual fields of measurement on each specimen, at a magnification of 200×. Each field of measurement in the grain size analysis sampled a range of 600–1200 and 200–500 grains for HPDC and step-cast, respectively.

3.3. Microindentation testing

A Micromaterials NanoTestTM (Wrexham, UK) microindentation hardness tester was used to perform indention on the specimens. A high-carbon steel sphere of 0.795 mm radius was used as the indenter. Eight partial cycles were performed during each test. The maximum indentation load achieved during each test was 18,000 mN. The indentation was performed with a loading, and unloading rate of 200 mN/s. Three indentations were made on each sample.

4. Experimental results

As shown in Fig. 1, in the case of step-casting, the grain morphology is shown to change from region 1 to region 3, as the cooling rate decreases. On moving away from the cooling end, the grains coarsen and elongate, giving a rise to dendritic structures. This is consistent with the theory of increase in the rate of grain coarsening with the decrease in cooling rate, due to lack of nucleation and consequently increased growth of the existing grains as shown in Table 2.

In HPDC, as can be seen in Fig. 2(a), the skin region contains refined grains, while in the core region (Fig. 2(b)), significantly larger grains, large primary Mg dendrites, and porosity are observed. The grain size has a significant variation in the core region, while it is relatively uniform in the skin region. As a result, the average grain size varies gradually from skin region to core region. It has been reported that the transition region from skin to core can be determined by a grain size threshold value of 10–11 μm [7].

Fig. 3 shows the load–depth curves of indentation tests performed on the skin and core region of HPDC and sample A cut from step-cast of magnesium alloy AE44. The skin region is shown to have comparatively higher indentation hardness than the HPDC core region and the step-casting sample A. Similar results are observed for the other two magnesium alloys examined in this study.

In the present study, the plasticity parameter, $\boldsymbol{\Phi}$, was found to be within the elastic–plastic transition zone (Fig. 4). These results can be used to acquire the constraint factor for the calculation of indentation stress. The average indentation stress, $\boldsymbol{\sigma_{avg}}$, was obtained from the indentation load–depth curve (Fig. 3) using Eq. (3) and Eq. (5). The indentation stress–strain curves in Fig. 5 show that there is a distinct difference, both in the magnitude of indentation stresses and the strain-hardening trend, between samples of the HPDC skin region and samples of step-cast.

The indentation yield point, $\boldsymbol{\sigma_y}$, at a plastic strain of zero, can be approximated by linear extrapolation of the $\boldsymbol{\sigma_{avg}}$, versus $\boldsymbol{\varepsilon_{avg}}$, plot as shown in Fig. 5. The power law functions were linearly extrapolated to $\boldsymbol{\varepsilon_{avg}} = 0$ (zero plastic strain), representing an initial yield stress. The indentation yield stress and tensile yield stress (Ref [7]) for each examined sample are presented in Fig. 6, showing the dependency of yield stress upon grain size.

5. Discussion

5.1. Microstructure-dependent local mechanical properties

There is an obvious difference in indentation response between samples of HPDC (skin and core regions) and step-casting for three types of magnesium alloys as shown in Figs. 3 and 5. This result can