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Research Letter

Strain-Hardening and Fracture Behavior of Die Cast Magnesium Alloy AM50

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Understanding tensile and fracture behaviors of die cast magnesium alloys is of importance for proper design of various emerging automotive applications. In the present study, magnesium alloy AM50 was high pressure die cast into rectangular coupons with section thicknesses of 2, 6, and 10 mm. Effect of section thicknesses on strain-hardening and fracture behaviors of the die cast AM50 was investigated. The results of tensile testing indicate that the tensile properties including yield strength (YS), ultimate tensile strength (UTS), and elongation (E_f) decrease with increasing section thicknesses of die cast AM50. The analysis of true stress versus strain curves shows that the straining hardening rates during the plastic deformation of the alloy increase with decreasing section thicknesses. The observation via SEM fractography illustrates that the fracture behavior of die cast AM50 is influenced by section thicknesses. As the section thickness increases, the fracture of AM50 tends to transit from ductile to brittle mode due to increasing porosity content and coarsening microstructure.

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1. INTRODUCTION

Magnesium usage in automobiles has arisen significantly due to consumer demands for increased performance and fuel economy of vehicles. Most magnesium applications presently used in the automotive industry are high-pressure die cast (HPDC), and have relatively good strength and high ductility at room temperature. Applications of HPDC magnesium alloys AM50, such as front-end support assemblies, steering wheel armatures, and steering column support brackets [1], have not only complex shapes but also cross-sections with various thicknesses. Very often, under normal die casting conditions, thick sections have a higher tendency to solidification shrinkage and porosity caused by inclusion of gas than thin walls. It has been indicated [2–4] that the porosity level of components can influence mechanical properties, such as ultimate tensile strength (UTS), 0.2% yield strength (YS), and elongation (E_f). However, detailed analyses on plastic deformation and fracture behaviors of die cast AM50 alloy with different section thicknesses are limited.

This paper presents an in-depth analysis of strain-hardening behavior during plastic deformation and fracture characteristics of die cast AM50 alloy with section thicknesses of 2, 6, and 10 mm. The influence of section thicknesses on plastic deformation behavior of the alloy was studied based on the analysis of true stress-strain relation. The fracture behavior of the die cast AM50 affected by section thicknesses was characterized by using SEM fractography.

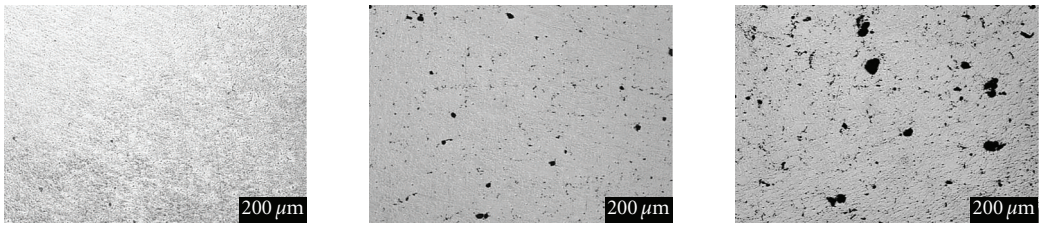
2. EXPERIMENTAL PROCEDURES

2.1. Alloy and casting preparation

The magnesium alloy selected in this study was die casting alloy AM50 (Mg-4.9 wt, %Al-0.39 wt, %−0.2 wt, % Zn). Flat rectangular coupons of 0.125 m × 0.027 m with different section thicknesses of 2 mm, 6 mm, and 10 mm were die cast on a 700-ton cold chamber horizontal high-pressure die casting machine. Detailed die casting conditions were given in [4].

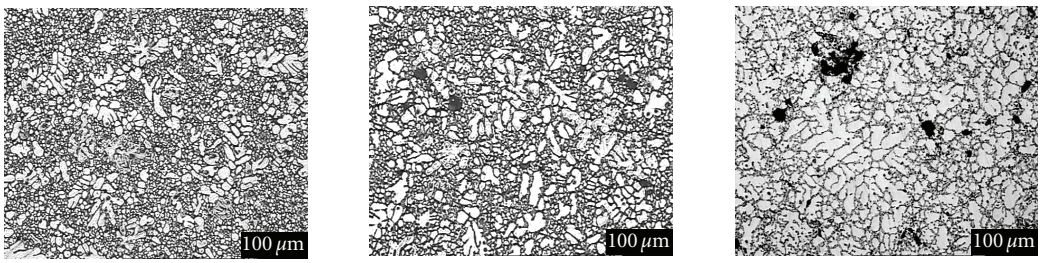
2.2. Tensile testing

The mechanical properties of the die cast AM50 alloy were evaluated by tensile testing, which was performed at ambient



(a) (b) (c)

Figure 1: Optical micrographs showing porosity in the die cast AM50 alloy with section thicknesses, (a) 2, (b) 6, and (c) 10 mm.



(a) (b) (c)

Figure 2: Optical micrographs showing microstructure of the die cast AM50 alloy with different section thicknesses, (a) 2, (b) 6, and (c) 10 mm.

temperature on an Instron machine equipped with a computer data acquisition system. Following ASTM B557, subsize flat tensile specimens (25 mm in gage length, 6 mm in width, and 2, 6, or 10 mm in as-cast thickness) were machined from the die cast coupons. The tensile properties, including 0.2% yield strength (YS), ultimate tensile strength (UTS), and elongation to failure (E_f), were obtained based on the average of three tests.

2.3. Characterization of microstructure and fractured surface

Specimens were sectioned, mounted, and polished from the centre of the die cast coupons and prepared following the standard metallographic procedures. The fractured surfaces of tensile specimens were analyzed to ascertain the nature of fracture mechanisms by A JSM-5800LV scanning electron microscope (SEM) with a maximum resolution of 100 nm in a backscattered mode/1 μm in X-Ray diffraction mapping mode, and maximum useful magnification of 30 000.

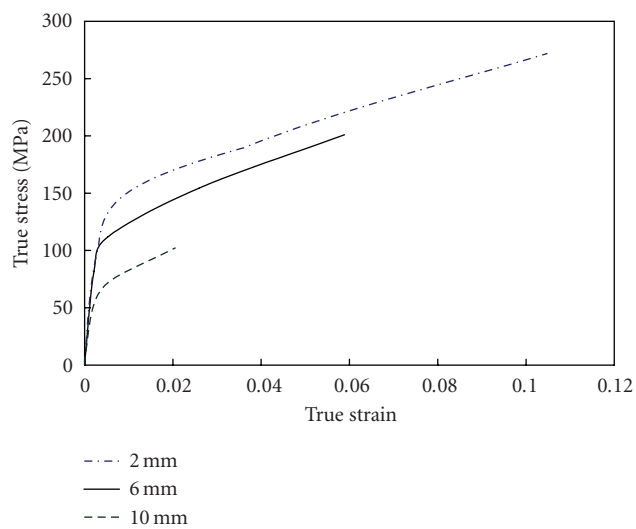


Figure 3: Typical true strain versus stress curves for the die cast AM50 alloy.

3. RESULTS AND DISCUSSION

3.1. Tensile behavior

The variation of engineering tensile properties including UTS, YS, and E_f with section thicknesses is compiled in Table 1. The UTS and YS decrease to 112.4 and 82.3 MPa for 10 mm thick specimens and to 240.2 and 133.7 MPa for the 2 mm coupons, which implies over 50% reduction in UTS and almost 40% decrease in YS, respectively. Moreover, the elongation values, 11.1%, 6.2%, and 2.3% for 2, 6, 10 mm, respectively, indicate evidently that a significant decrease in elongation occurs when the section thickness of specimens increases. The results of the current study are consistent with the relationship between tensile properties and section thicknesses for different types of die casting magnesium alloys reported in the literature [5, 6]. Figures 1 and 2 reveal the porosity distribution and microstructure of the die cast AM50 alloys with 2, 6, and 10 mm section thicknesses, respectively.

The experimental observation indicates that there are differences in casting soundness in terms of the porosity level

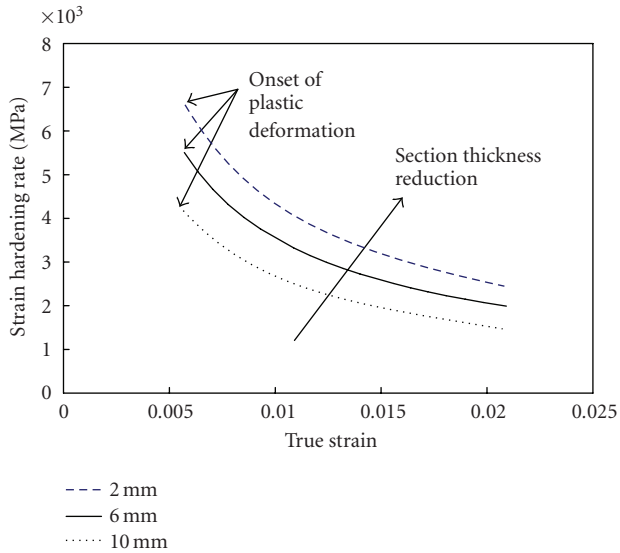


Figure 4: Strain-hardening rate versus true strain for plastic deformation of the die cast AM50 alloy.

and grain structure among the die cast AM50 alloys with three section thicknesses. The considerably low porosity level of the 2 mm thick coupon compared with the 6 and 10 mm specimens may be attributed to the die design which resulted in minimized turbulent cavity filling flow, and high solidification rates taking place in the thin specimens. Also, it is understood that, due to its heavy wall thickness, the 10 mm thick specimen solidified at a considerable slower rate than that of the 2 and 6 mm coupons. Consequently, the significantly coarse microstructure developed in the 10 mm thick specimen compared to that formed in the 2 and 6 mm ones. Differences in the porosity level and the microstructure of die cast AM50 could be responsible for the deviation in strengths and elongation. The fine microstructure and low-porosity level of thin specimens enhance their tensile properties. More details on microstructure analyses are also given in [2, 4].

The relatively low strengths and elongations of thick specimens result from the coarse microstructure, thin skin layer, high-porosity level in the center, and the presence of large pores. This experiment observation is consistent with the findings presented in [7, 8]. The study by Abbot et al. [7] on die cast magnesium alloys AM60, AZ91D, and AS21 also shows that the tendency in tensile properties was for a shift in the flow curves of thinner samples to higher stress levels. Sequeira [8] investigated the skin effect in flat die castings by the removal of the skin from 1 mm thick flat die cast AZ91D tensile specimens. The skin removal led to a considerable drop in yield strength from 185 MPa to 159 MPa, which indicates that the skin is at least partially responsible for its high tensile properties.

Figure 3 shows representative true stress and strain curves of the die cast AM50 alloy. For all three section thicknesses of specimens, the stress varies with the strain in similar pattern. Under tensile loading, the alloy deformed elastically first. Once yield points were reached, plastic deformation of the alloy sets in. However, the 2 mm thick specimens fractured at high-stress and -strain levels compared to the 6 and 10 mm thick specimens.

Table 1: Engineering tensile properties of the die cast AM50 alloy at room temperature.

Section thickness (mm)	Ultimate tensile strength (UTS) (MPa)	Yield strength (YS) (MPa)	Elongation (E_f) (%)
2	240.2 ± 6.1	133.7 ± 3.2	11.1 ± 1.3
6	187.8 ± 4.7	113.2 ± 2.8	6.2 ± 0.7
10	112.4 ± 3.6	82.3 ± 1.6	2.3 ± 0.5

Table 2: Best fit parameters for power equations.

Section thickness (mm)	K (MPa)	n	R^2
2	445.53	0.245	0.96
6	389.99	0.235	0.98
10	249.19	0.226	0.99

The stress-strain curve for metals is often described by the power expression [9]

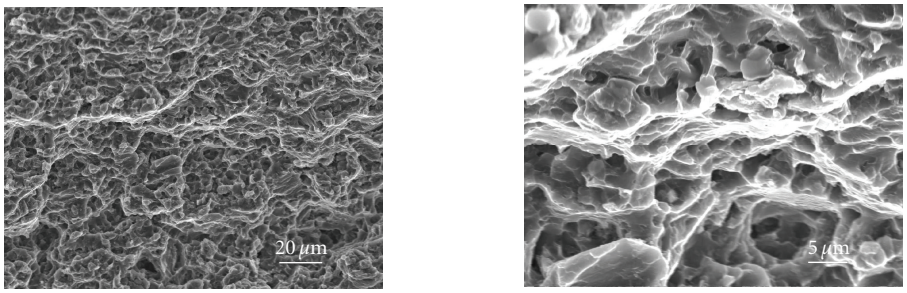
$$\sigma = K\varepsilon^n, \tag{1}$$

where K and n are empirical constants. The regression analysis indicates that the power expression is in reasonable agreement with the tensile results. The numerical values of these constants in (1) with the regression coefficients are listed in Table 2. Equation (1) can be differentiated to obtain strain-hardening rates ($d\sigma/d\varepsilon$).

The strain-hardening behaviors of the die cast AM50 alloy are illustrated in a plot of strain-hardening rate ($d\sigma/d\varepsilon$) versus true plastic strain (ε) during the plastic deformation as shown in Figure 4, which is derived from Figure 3. The 2 mm alloy has a high strain-hardening rate (7000 MPa) with respect to the thick 10 mm specimen (4000 MPa) at the onset of plastic deformation. It is evident that, for all three section thicknesses, their strain-hardening rates decrease with increasing true strain. Moreover, the strain-hardening rate during the plastic deformation of the die cast alloy varies also with section thickness. As the section thickness decreases, the strain-hardening rate increases. This observation implies that, compared to the 6 and 10 mm thick samples, the die cast AM50 alloy with the thin cross-section (2 mm) is capable of spontaneously strengthening itself increasingly to a large extent, in response to extensive plastic deformation prior to fracture. The low-porosity level and the even dispersion of fine intermetallic particles inside grains and around grain boundaries observed by Zhou et al. [2, 4, 10], which resist slip in the primary phase, should be responsible for the relatively high strain-hardening rate of the thin alloy in the early stage of plastic deformation, that is, instantly after the onset of plastic flow as indicated in Figure 4.

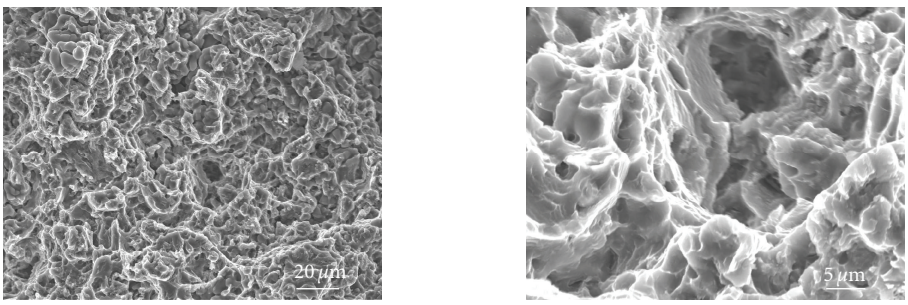
3.2. Fracture characteristics

Examination of the fracture surfaces of tensile specimens via SEM manifests the fracture behavior of die cast AM50 with three different thicknesses, which is shown in Figures 5–7.



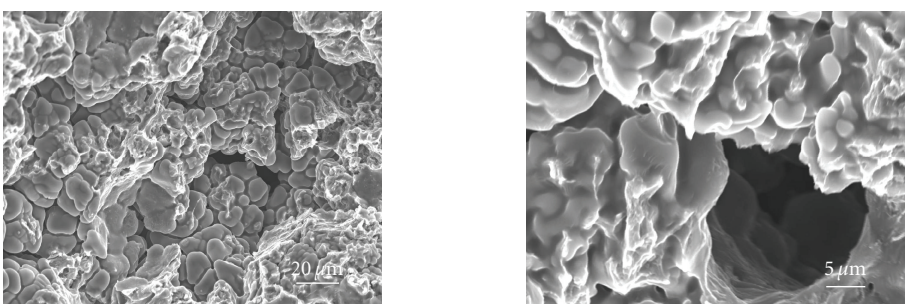
(a) (b)

Figure 5: SEM fractographs of 2 mm thick die cast coupon, (a) low and (b) high magnifications.



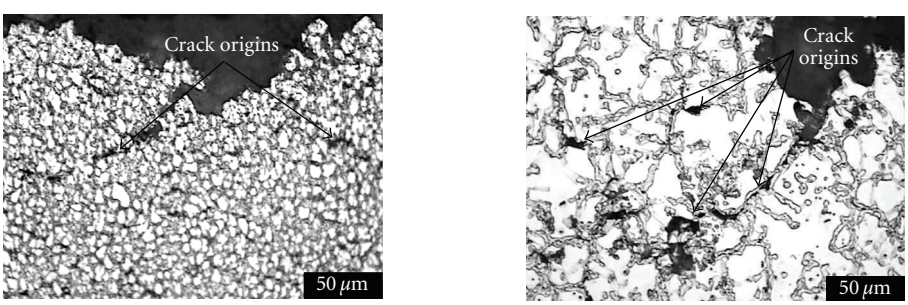
(a) (b)

Figure 6: SEM fractographs of 6 mm thick die cast coupon, (a) low and (b) high magnifications.



(a) (b)

Figure 7: SEM fractographs of 10 mm thick die cast coupon, (a) low and (b) high magnification.



(a) (b)

Figure 8: Optical micrograph showing microstructure underneath the fractured surface of (a) 2, and (b) 10 mm thick coupons.

Certain areas were observed under a high magnification in an attempt to reveal detailed features of fracture surface and determine the manner where the primary crack originated. The analysis of SEM fractography shows that the fracture behavior of die cast AM50 is influenced by the section thicknesses. As the section thickness increases, the fracture of AM50 tends to transit from ductile to brittle mode.

The fracture surfaces of the 2 and 6 mm thick specimens illustrated in Figures 5 and 6 are primarily ductile in nature, which are characterized by the presence of deep dimples. The fractographs with a higher magnification, Figures 5(b) and 6(b), portray the dimples with extensive deformation marking along the walls of individual craters. A considerable amount of energy is consumed in the process of the formation of microvoids and microvoid sheet, eventually leading to the creation of cracks. Thus, this type of fracture failure results from the coalescence of microvoids under the tensile stress. It seems, however, that the failure of the 10 mm thick specimen is caused by a brittle fracture mechanism of combined void coalescence and intergranular fracture as shown in Figure 7. A similar mechanism for the fracture of die cast magnesium alloy AZ91D has also been reported in [11]. The initiation point of cracks began with the internal discontinuity due to the presence of porosity. The final fracture results from the growth and coalescence of the cracks. The brittle eutectic β-$Mg_{17}Al_{12}$ segregation along the grain boundaries should be the main cause of the intergranular fracture. The damaged microstructure underneath the fractured surfaces presented in Figure 8, at least in part, supports this interpretation. Overall, the SEM observations of the fracture surfaces show a good agreement with the ductility data given in Figure 3 and Table 1.

4. CONCLUSIONS

The strain-hardening and fracture failure of the high-pressure die cast magnesium alloy AM50 are influenced by its section thickness. The results of tensile testing indicate that the mechanical properties, UTS, YS, and E_f, increase significantly with a reduction in the section thickness of the alloy. The analysis of plastic deformation behavior reveals that an increase in high strain-hardening rates of the alloy with decreasing the section thickness enables the alloy to spontaneously strengthen the materials increasingly to a large extent, in response to extensive plastic deformation prior to fracture. The observation via SEM fractography illustrates that the fracture behavior of die cast AM50 is influenced by the section thickness. As the section thickness increases, the fracture of AM50 tends to transit from ductile to brittle mode. Cracks primarily initiate at the internal discontinuities due to the presence of porosity.

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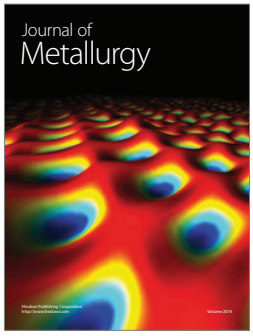

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