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Microstructure and Tensile Properties of Squeeze Cast Magnesium Alloy AM50

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High-pressure die cast magnesium alloy AM50 is currently used extensively in large and complex shaped thin-wall automotive components. For further expansion of the alloy usage in automobiles, novel-manufacturing processes need to be developed. In this study, squeeze casting of AM50 alloy with a relatively thick cross section was carried out using a hydraulic press with an applied pressure of 70 MPa. Microstructure and mechanical properties of the squeeze cast AM50 with a cross-section thickness of 10 mm were characterized in comparison with the die cast counterpart. The squeeze cast AM50 alloy exhibits virtually no porosity in the microstructure as evaluated by both optical microscopy and the density measurement technique. The results of tensile testing indicate the improved tensile properties, specifically ultimate tensile strength and elongation, for the squeeze cast samples over the conventional high-pressure die cast parts. The analysis of tensile behavior show that the strain-hardening rate during the plastic deformation of the squeeze cast specimens is constantly higher than that of the die cast specimens. The scanning electron microscopy fractography evidently reveals the ductile fracture features of the squeeze cast alloy AM50.

Keywords automotive, casting, mechanical testing, non-ferrous metals

1. Introduction

Magnesium alloys are the lightest of all the commonly used metals, offer excellent die castability, and are thus very attractive for applications in the automobile industry. In the past few years, with the rapid expansion of magnesium applications in the automotive industry, large-scale thin-wall die cast body-on-frame magnesium components have been developed and implemented by taking full advantage of high-pressure die casting processes (Ref 1). However, high-pressure die castings have relatively high-gas porosity levels, particularly in an area with relatively thick cross section, due primarily to the entrapment of air or gas in the melt during the high-speed injection of turbulent molten metal into the cavity. It has been indicated (Ref 2-4) that the section thickness of magnesium die castings has a great influence on their microstructure and tensile properties including yield strength (YS), ultimate tensile strength (UTS), and elongation. An increase to 10 from 2 mm in the section thickness of magnesium die castings reduces their tensile properties significantly. This is attributed to the presence of a large amount of porosity and coarse microstructure resulting from high tendency of gas entrapment in thick magnesium coupons and low solidification rate during the high-pressure die casting process.

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Squeeze casting is a process that involves slow laminar filling and the solidification of a molten metal in a closed die under an imposed high pressure. Other terms used to describe the same or similar processes are liquid metal forging, extrusion casting, and pressure crystallization. The high-applied pressure, which is several orders of magnitude greater than the melt pressure developed in normal casting processes, keeps entrapped gases in solution and squeezes molten metal from hot spots to incipient shrinkage pores. As a result, the porosity in a squeeze cast component is almost eliminated. Furthermore, due to the elimination of the air gap at the liquid-mold interface by the applied high pressure, the heat transfer across die surfaces is enhanced, which increases solidification and cooling rates. Consequently, superior tensile properties of the casting resulting from the pore-free fine microstructure can be achieved in squeeze casting processes. In addition, the adverse effect of section thickness could potentially be minimized on tensile properties (Ref 5, 6). However, limited information on squeeze casting of AM50, one of the most common magnesium alloys, is available in the open literature.

This article presents the progress of an ongoing research work on squeeze casting of magnesium alloy AM50. The microstructure, tensile behavior, and fracture behavior of squeeze cast AM50 alloy are studied. The informative results are compared with those for the identical alloy, which was high-pressure die cast. The structure-property relationship and the mechanism of property enhancement are also discussed.

2. Experimental Procedures

2.1 Alloy and Casting Preparation

The magnesium alloy selected for this study is the conventional magnesium alloy AM50, of which chemical composition is listed in Table 1. Cylindrical coupons Φ 95 mm with a section thickness of 10 mm were squeeze cast. The squeeze casting experiments started with the transfer of a metered quantity of molten magnesium AM50 alloy (690 °C) into the bottom half of the preheated (400 °C) die set mounted in a hydraulic press. The dies were then closed, with the top half (punch) lowering into the bottom die. The pressure exerted by the punch on the molten metal is steadily increased to a predetermined level of approximately 70 MPa and maintained until the entire casting has solidified. For the purpose of comparison, flat rectangular coupons (0.125 × 0.027 m) of AM50 with a section thickness of 10 mm were die cast on a 700 ton cold chamber horizontal high pressure die casting machine. During die casting, the die temperature was set at 350 °C and the melt temperature at 690 °C.

2.2 Porosity Evaluation

Porosity was evaluated via density measurement. Following the measurement of specimen weight in the air and distilled water, the actual density (D_a) of each specimen was determined using Archimedes principle based on ASTM Standard D3800 (Ref 7):

$$D_a = \frac{W_a D_w}{W_a - W_w} \quad \text{(Eq 1)}$$

where W_a and W_w are the weight of the specimen in the air and in the water, respectively, and D_w the density of water.

The porosity of each specimen was calculated by the following equation (ASTM Standard C948) (Ref 8):

$$\% \text{ Porosity} = \left[\frac{D_t - D_a}{D_t}\right] \times 100\% \quad \text{(Eq 2)}$$

where D_t is the theoretical density of the alloy AM50, which is 1.77 g/cm^3 (Ref 9).

2.3 Microstructural Analysis

Specimens were sectioned, mounted, and polished from the center of the squeeze disk and the die cast coupons and prepared following the standard metallographic procedures. A Buehler (Lake Bluff, IL) optical image analyzer 2002 system was used to determine primary characteristics of the specimens. The detailed features of the microstructure were also characterized at high magnifications by A JSM-5800LV (Tokyo, Japan) 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. To maximize composition reading of the energy dispersive spectroscopy (EDS) data, an etchant was applied to polished specimens for microscopic examination. Fractured surfaces of tensile specimens were analyzed by the SEM to ascertain the nature of fracture mechanisms.

2.4 Tensile Testing

The mechanical properties of the squeeze cast and die cast AM50 alloys were evaluated by tensile testing, which was performed at ambient temperature on an Instron (Grove City, PA) machine equipped with a computer data acquisition system. Following ASTM B557 (Ref 10), subsize flat tensile specimens (25 mm in gage length, 6 mm in width, and 10 mm in as-cast thickness) were machined from the squeeze cast disks and 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.

3. Results and Discussion

3.1 Porosity Evaluation

Figures 1 and 2 reveal the porosity distribution in the polished die cast and squeeze cast AM50 alloys through the op-

Table 1 Chemical composition of AM50

Alloy	Al	Zn	Mn	Si	Cu	Fe	Ni	Others
AM50	5%	<0.22%	0.4%	<0.1%	<0.01%	<0.004%	<0.002%	<0.01%

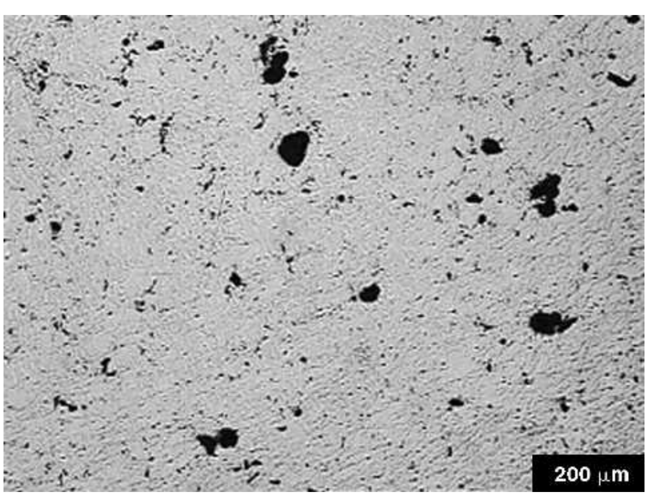

Fig. 1 Optical micrograph showing porosity in die cast AM50 alloy with a section thickness of 10 mm

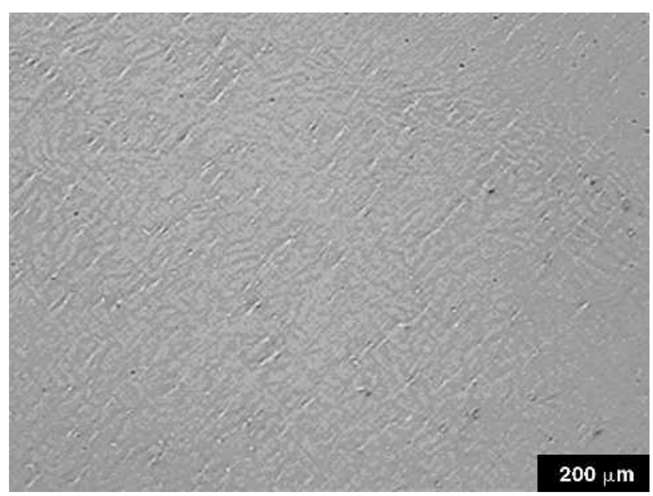

Fig. 2 Optical micrograph showing almost porosity-free squeeze cast AM50 alloy with a section thickness of 10 mm

Fig. 3 Porosity levels of squeeze cast and die cast AM50 with a section thickness of 10 mm

tical microscopy examination, respectively. Representative pores can be easily spotted in the die cast plates of AM50 alloy with a section thickness of 10 mm as indicated in Fig. 1. However, it is evidently shown in Fig. 2 that the squeeze cast AM50 with the same section thickness is virtually free of gas and shrinkage porosities. Figure 3 presents quantitatively the percentage of the porosity of both the squeeze cast and die cast AM50 alloys, based on the density measurements. In comparison with that (4.00%) of the die casting, the porosity level of the squeeze castings is only 0.12%. The difference in casting soundness in terms of the porosity level between squeeze casting and die casting is evident, which is consistent with the observation of their microstructure.

The porosity elimination of squeeze casting should be attributed primarily to the high-applied pressure during solidification and low filling velocity during mold filling. The purpose of the low filling velocity is to avoid air entrapment, which usually occurs in the die casting process due to turbulent mold filling at high velocity. The high applied pressure suppresses gas porosity and reduces the shrinkage porosity by squeezing the semiliquid metal through a network of solid skeleton in the last region of the casting to solidify, which has been demonstrated in the previous work (Ref 5, 6, 9).

3.2 Microstructure

Figure 4 shows the microstructure of the etched die cast AM50 coupon with a section thickness of 10 mm revealed by optical microscopy. Its microstructure mainly consists of primary αMg grains and eutectic phases surrounding their boundaries. The size of primary αMg grains is around 40 μm, which is relatively large compared with the reported value for conventional die cast magnesium castings with a thin cross-section wall in the literature (Ref 3, 11, 13). This is primarily due to the somewhat slow solidification rate-taking place in the current thick die cast AM50 coupons. SEM results (Fig. 5) display the $\beta Mg_{17}Al_{12}$ eutectic phase (bright contrast), which is present in a matrix (dark contrast) of the primary αMg solid solution and tends to form a network surrounding the primary phase. Three different types of intermetallics labeled A, B, and C (white spots) were identified by EDS analysis. Figure 6 illustrates the EDS spectra for A, which is the αMg matrix, B as $\beta Mg_{17}Al_{12}$ phase, and C as Al-Mn intermetallic, which are almost identical to those reported in Ref 12-14.

The microstructure of the squeeze cast specimens with a 10 mm section thickness is shown in Fig. 7. The morphology

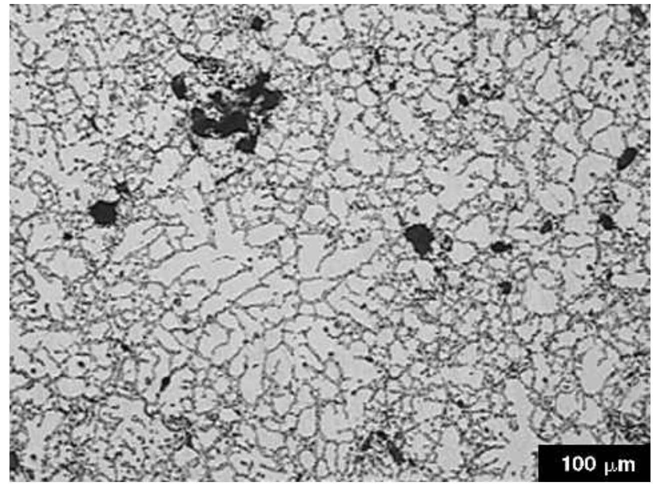

Fig. 4 Optical micrograph showing microstructure in die cast AM50 alloy with a section thickness of 10 mm

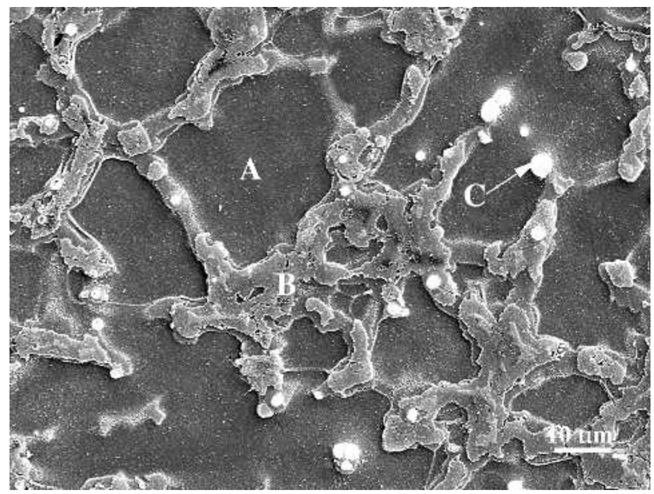

Fig. 5 SEM micrograph showing microstructure of die cast parts in as-cast condition

and distribution of the intermetallic phases are completely different from those present in the die cast AM50. Instead of forming a network, the intermetallics in the squeeze cast coupon are present in the form of isolated fine particles. Compared with those of the correspondent die cast specimens, the grain size of the squeeze cast specimens is slightly large around 56 μm. This is because the die temperature (400 °C) used in the squeeze casting process is somewhat higher than that (350 °C) of die casting in this study. In general, heat transfer across die surfaces is enhanced with the high-applied pressure, which eliminates air gaps at mold-liquid metal interface. However, a relatively low temperature difference between the mold and liquid metal in the squeeze casting could offset the enhancement of heat transfer resulting from the elimination of air gaps. As a result, the slow solidification rate of squeeze casting compared with that in die casting may be responsible for its relatively coarse grain structure.

Figure 8 reveals the presence of two types of the intermetallics in the squeeze cast specimens by SEM. The results of EDS analysis as depicted in Fig. 9 confirm that they are $\beta Mg_{17}Al_{12}$ (marked B) phase and Al-Mn intermetallic (labeled

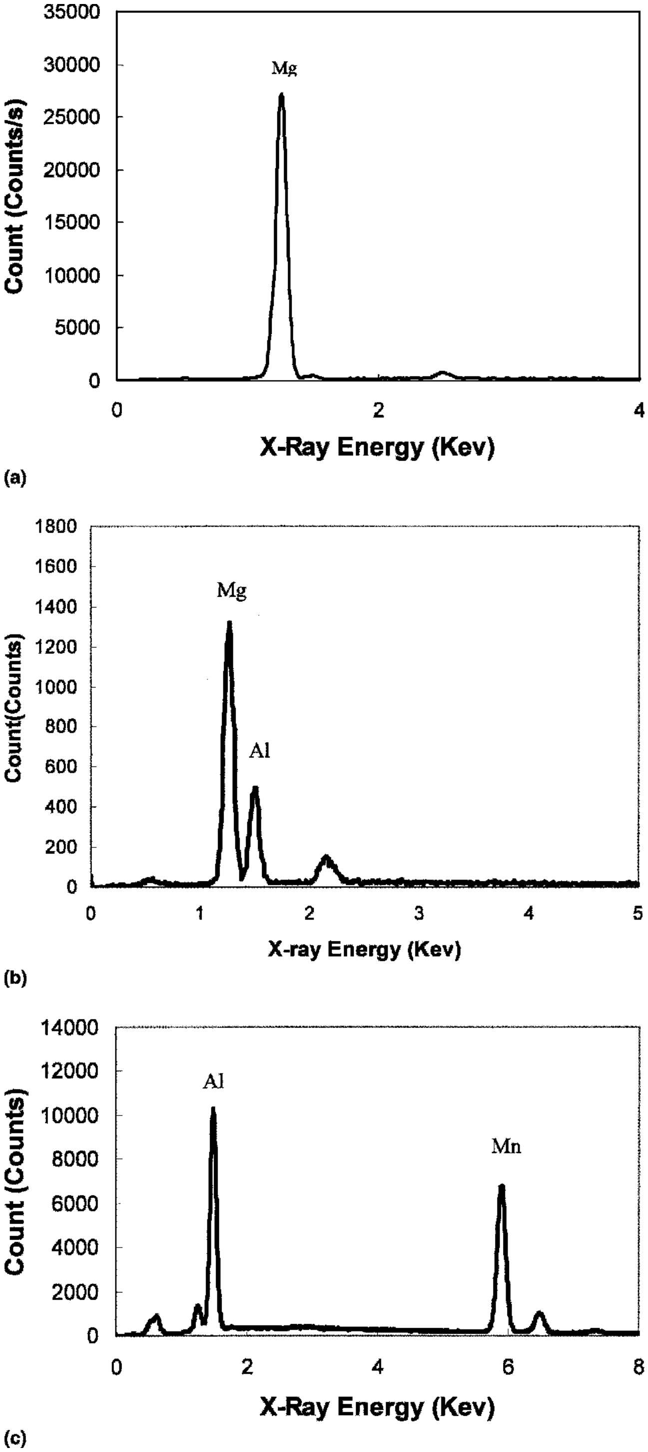

Fig. 6 EDS spectra (a), (b), and (c) for the regions marked A, B, and C in Fig. 5, respectively.

C), which are similar to those in the die cast coupon. However, the intermetallics in the squeeze cast coupon are distributed not only at grain boundaries but also inside primary α grains (marked A in Fig. 9), which are different from those in the die cast specimen.

3.3 Tensile Behavior

The representative true stress-strain curves obtained from tensile testing of both the die cast and squeeze cast AM50 alloys with 10 mm section thickness are shown in Fig. 10, and the corresponding tensile property data are summarized in Table 2. It can be seen from Fig. 10 that the slope of the linear portion of the curve for squeeze cast AM50 has a rising trend similar to that of the die cast alloy. Figure 10 and Table 2 also indicate that the yield strength for both the die cast and squeeze cast specimens is at a comparable level around 80 MPa on average. The elongation of the squeeze cast AM50 specimens is 8.0%, and the elongation of the die cast AM50 specimens is only 2.1%, signifying an increase of 281% over that of the die cast AM50 for as-cast conditions. During tensile testing, no necking phenomenon was observed for the die cast material before fracture, whereas a remarkable necking occurred in the squeeze cast specimens. Moreover, the UTS of the squeeze cast specimens is 175 MPa on average, which is 75% higher than that of the die cast alloy (100 MPa). A significant improvement on tensile properties of the squeeze cast AM50 alloy over the die cast counterpart is primarily attributed to the extremely low level of porosity present in the squeeze cast specimens with a comparable size of grains.

The strain-hardening behaviors of both the die cast and squeeze cast AM50 alloys can be clearly seen in a plot of

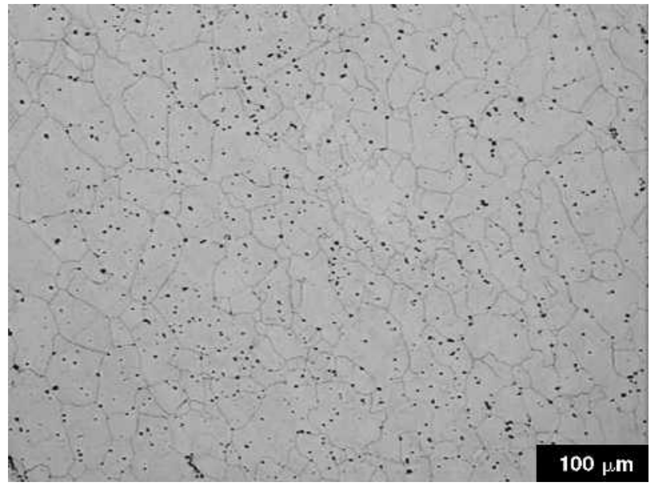

Fig. 7 Optical micrograph showing microstructure in squeeze cast AM50 alloy with a section thickness of 10 mm

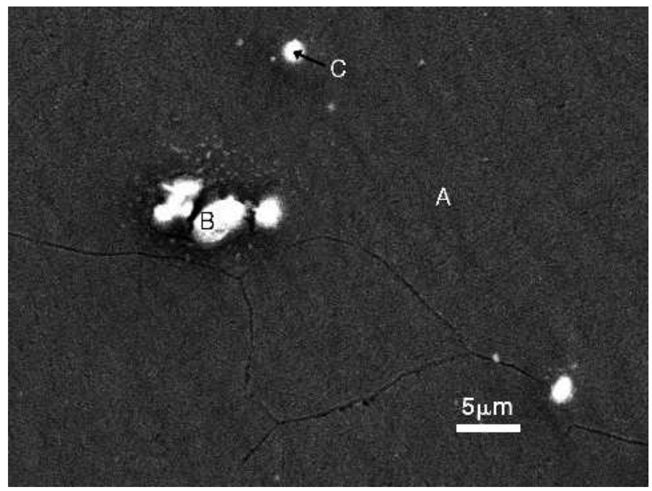

Fig. 8 SEM micrograph showing microstructure of squeeze cast coupons in as-cast condition

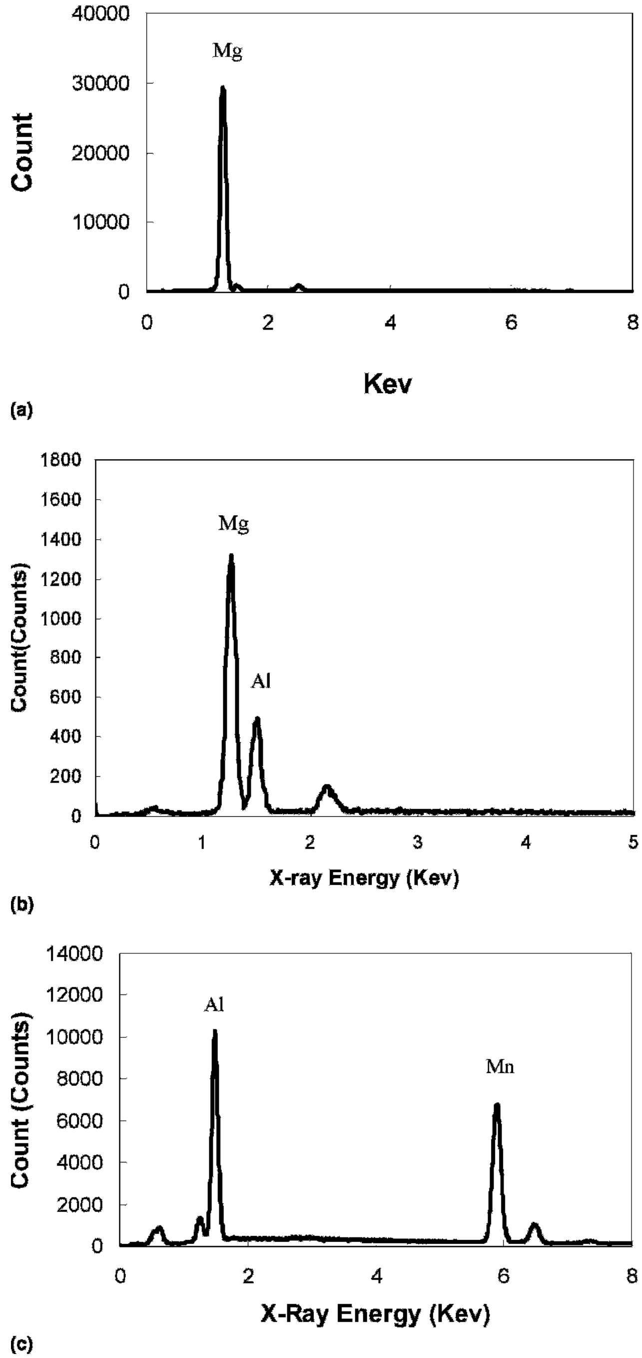

Fig. 9 EDS spectra (a), (b), and (c) for the regions marked A, B, and C in Fig. 8, respectively

strain-hardening rate (dσ/dε) versus true plastic strain (ε) during the plastic deformation, as shown in Fig. 11, which is derived from Fig. 10. It is evident that the strain-hardening rate during the plastic deformation, of the squeeze cast specimens is constantly higher than that of the die cast specimens. This implies that, compared with the die cast one, the squeeze cast AM50 is able spontaneously to strengthen itself increasingly to a large extent, in response to extensive plastic deformation prior to fracture. The considerably high strain-hardening rate of the squeeze cast AM50 in the early stage of plastic deformation, i.e., instantly after the onset of plastic flow as indicated in Fig. 11, may be attributed to the absence of porosity and the

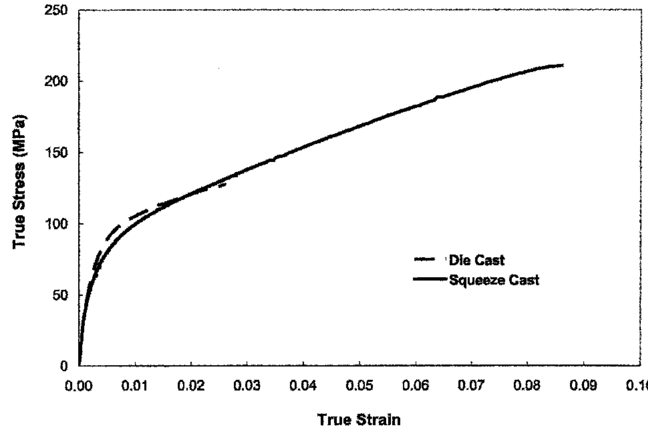

Fig. 10 Representative true stress versus strain curves for squeeze cast and die cast AM50 alloys

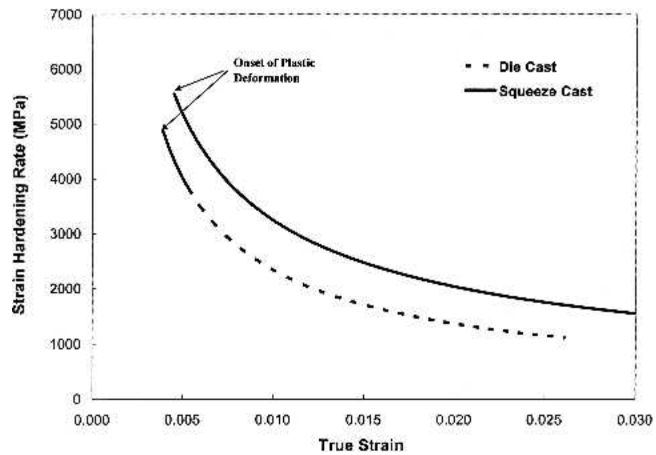

Fig. 11 Strain-hardening rate versus true strain for plastic deformation of squeeze cast and die cast AM50 alloys

Table 2 Tensile properties of AM50 alloy with 10 mm section thickness at room temperature

Casting condition	0.2% YS, MPa	UTS, MPa	Elongation, %
Squeeze cast	75	175	8.0
Die cast	80	100	2.1

even dispersion of fine intermetallic particles inside grains and around ground boundaries, which resist slip in the primary phase. To apply the squeeze cast AM50 for engineering applications, its strengthening mechanisms should be further investigated in detail.

3.4 Fracture Behavior

The differences in the fracture behaviors between the die cast and squeeze cast AM50 alloys are evidently revealed in Fig. 12 and 13 by the SEM fractography. Figure 12 shows a typical fracture surface of the squeeze cast AM50, which is primarily ductile in nature. The observed fracture mode of the squeeze cast specimens in as-cast conditions is quasi-cleavage as illustrated in Fig. 12(a). The characteristic feature of cleav-

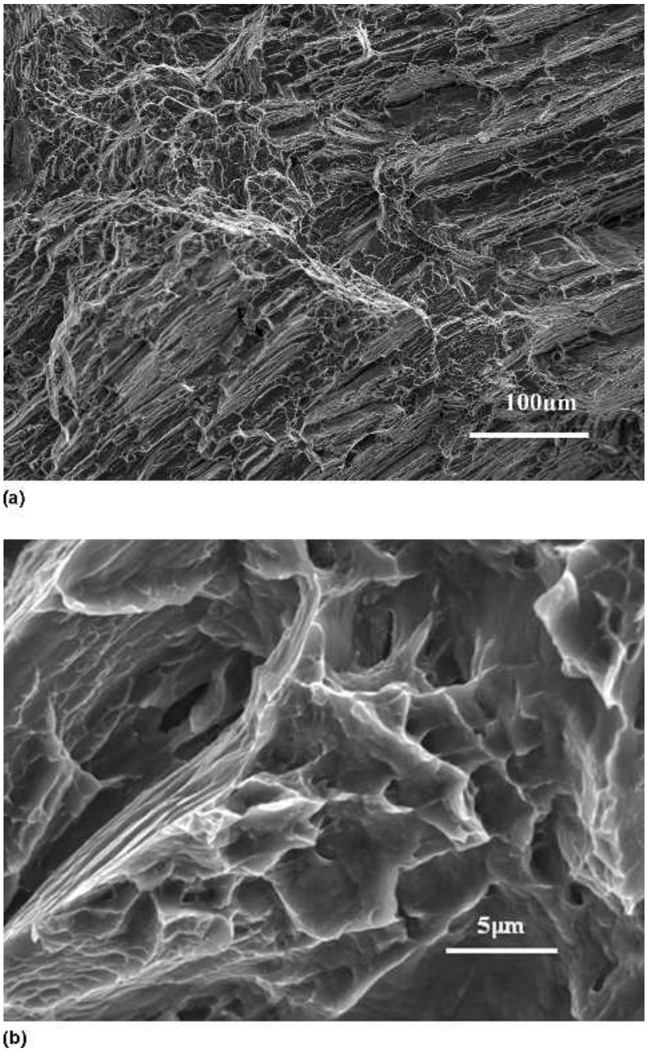

Fig. 12 SEM fractographs of squeeze cast AM50. (a) low magnification and (b) high magnification

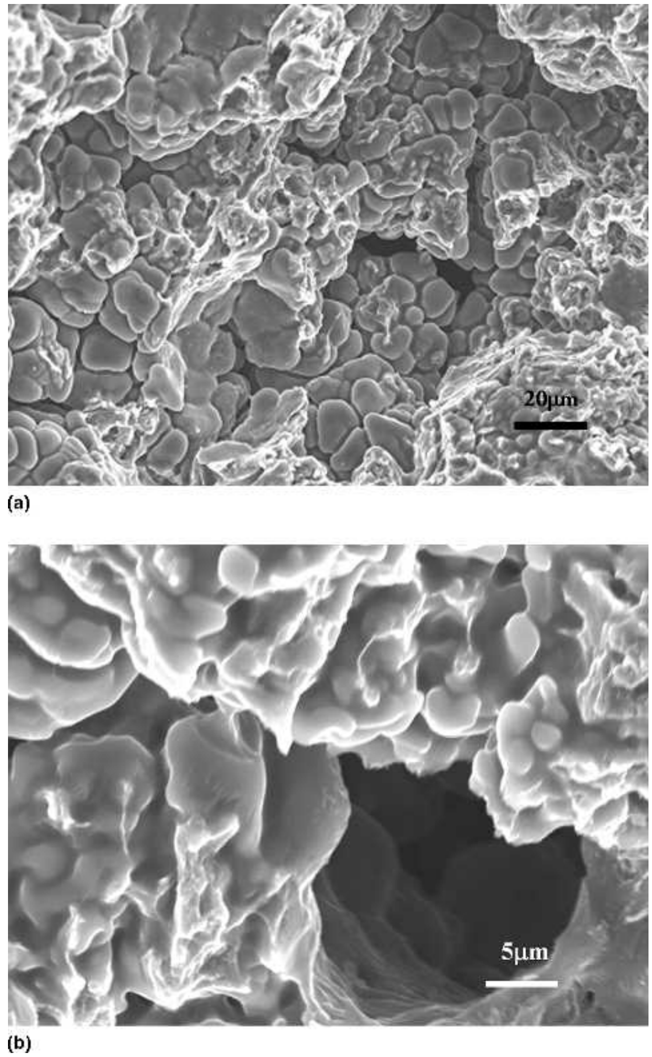

Fig. 13 SEM fractographs of die cast AM50. (a) low magnification and (b) high magnification

age fracture, flat facets, is observed on these fracture surfaces. The flat facets are covered fully and partially by river markings and dimples on the fracture surface of the squeeze cast specimen. The river marking is the result of the crack moving through the grain along a number of parallel planes, which forms a series of plateaus and connecting ledges. The dimples are caused by the localized microvoid coalescence. These features are an indication of the absorption of energy through local deformation. The entire fracture surface of the squeeze cast specimen in as-cast condition is characterized by the presence of deep dimples. The fractograph with higher magnification, Fig. 12(b), portrays 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. However, the tensile fracture surface of the die cast AM50 alloy with 10 mm section thickness, as shown in Fig. 13, is somewhat brittle in nature. It is evident that the failure of the die cast specimens is caused by a combined brittle fracture mechanism of void coalescence and intergranular fracture. An internal discontinuity due to the presence of porosity serves as the initiation point of cracks in the die cast specimens. The growth and coalescence of the cracks result in the final fracture. In the region away from the porosities, the failure is mainly attributed to the intergranular fracture, which is depicted in Fig. 13(a). The cause of this intergranular fracture is the segregation the brittle eutectic β phase ($Mg_{17}Al_{12}$) at grain boundaries. In general, the results of the SEM fractography for both the squeeze cast and die cast AM50 alloys are in good agreement with the data of tensile properties listed in Table 2. The elimination of porosity in AM50 is mainly responsible for the difference in fracture modes between the squeeze cast and die cast AM50 alloys.

4. Conclusions

Squeeze casting as a novel manufacturing process is capable of eliminating porosity in magnesium alloy AM50 with a relatively thick cross section compared with high-pressure die casting. Squeeze cast AM50 shows attractive tensile properties. Significant improvement in elongation (281%) and UTS (75%) of the squeeze cast AM50 over the die cast one has been achieved. This is primarily attributed to the extremely low level of porosity present in the squeeze cast specimens with a comparable size of grains. Higher strain-hardening rates of the squeeze cast specimens than those of the die cast ones indicate that the squeeze cast AM50 is able to spontaneously strengthen itself increasingly to a large extent, in response to extensive plastic deformation prior to fracture. The SEM analysis of fracture surfaces shows that the squeeze cast AM50 displays the characteristics of ductile fracture, whereas the die cast one exhibits brittle fracture modes. The elimination of porosity in AM50 is mainly responsible for the difference in fracture modes between the squeeze cast and die cast AM50 alloys.

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