# Section thickness-dependent tensile properties of squeeze cast magnesium alloy AM60

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**Abstract:** The development of alternative casting processes is essential for the high demand of light weight magnesium components to be used in the automotive industry, which often contain different section thicknesses. Squeeze casting with its inherent advantages has been approved for the capability of minimizing the gas porosity in magnesium alloys. For advanced engineering design of light magnesium automotive applications, it is critical to understand the effect of section thickness on mechanical properties of squeeze cast magnesium alloys. In this study, magnesium alloy AM60 with different section thicknesses of 6, 10 and 20 mm squeeze cast under an applied pressure of 30 MPa was investigated. The prepared squeeze cast AM60 specimens were tensile tested at room termperature. The results indicate that the mechanical properties including yield strength (YS), ultimate tensile strength (UTS) and elongation (*A*) decrease with an increase in section thickness of squeeze cast AM60. The microstructure analysis shows that the improvement in the tensile behavior of squeeze cast AM60 is primarily attributed to the low-gas porosity level and fine grain strucuture which result from the variation of cooling rate of different section thickness. The numerical simulation (Magmasoft®) was employed to determine the solidification rates of each step, and the simulated results show that the solidification rate of the alloy decreases with an increase in the section thickness. The computed solidification rates support the experimental observation on grain structural development.

**Key words:** squeeze casting; magnesium alloy AM60; tensile properties; section thickness

CLC numbers: TG 146.2$^{+}$2　　Document code: A　　Article ID: 1672-6421(2012)02-178-06

The use of magnesium has grown dramatically in the automotive industry since the early 1990s. The growth is expected to continue as new applications are developed. The U.S. Automotive Material Project (USAMP) in 2006 predicted that the use of magnesium is expanding from 10–12 to 350 lbs/vehicle, substituting for 630 lbs of steel and aluminum. These components were used in instrument panel support beams, driver-side instrument panel support castings and steering wheel armatures, cam covers, and steering column jackets. The increasing use of magnesium mainly attributes to the demands for lightweight and fuel economy of vehicles. Magnesium is one-third lighter than aluminum, three-fourths lighter than zinc, and four-fifths lighter than steel. Moreover, the combination of high specific strength and stiffness, and excellent castablity, high die casting rate and high dimensional accuracy qualify this interesting lightweight metal in the automotive industry [1].

Magnesium components currently used in the automotive industry are produced by high-pressure die casting (HPDC) process, which is well-established, widely used and cost-effective. But, it is only suitable for producing thin-walled parts [2]. However, potential applications of magnesium alloys on automotive could involve cross sections with different wall thicknesses and complex shapes. The problem found in HPDC thick-walled sections is porosity caused by filling turbulence and solidification shrinkage. The previous works have indicated that the porosity level has strong influences on mechanical properties, such as ultimate tensile strength (UTS), yield strength (YS) and elongation (*A*) [3, 4]. Thus, squeeze casting (SQC) is designed for production of relatively thick-walled parts with fine microstructure by means of slow filling velocity, semi-solid processing and solidification under high pressure.

Squeeze casting is termed to describe a process that involves the solidification of a molten metal in closed die under an imposed high pressure [5–6]. This process has been successfully

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**Received: 2011-06-10; Accepted: 2011-08-12**

applied in the production of aluminum components in automotive industry, such as engine blocks, road wheels and knuckles. However, magnesium components have not been widely produced by squeeze casting. In order to compete with aluminum and other materials in automotive industry, magnesium fabrication technique must be varied and to extend the limits imposed by the current and traditional gravity and die casting technologies. The development of squeeze casting technology for magnesium alloys [7–9] will enhance the competitiveness of magnesium components in the growing automotive market.

In this work, magnesium alloy AM60 was squeeze cast under an applied pressure of 30 MPa. The microstructure and tensile behaviour of alloy AM60 was studied, and their relations with section thickness were presented. The mechanisms responsible for the resulted tensile properties were discussed based on the SEM microstructural characterization as well as the numerical prediction of solidification rates.

## 1 Experimental procedure

A step mold made of tool steel was used to fabricate step squeeze castings. The thicknesses of each step were 6 mm, 10 mm and 20 mm. The magnesium alloy selected for this work was the conventional magnesium alloy AM60. This alloy was used to produce three-step castings without any addition. The nominal chemical composition for this alloy is presented in Table 1. The detailed experimental procedure of squeeze casting is given in Ref. [9].

**Table 1: Chemical composition of the investigated AM60 alloy (wt.%)**

| Al | Mn | Si | Fe | Mg |
|---|---|---|---|---|
| 5.93 | 0.18 | < 0.02 | 0.013 | Bal. |

The mechanical properties of the squeeze cast AM60 were evaluated by tensile testing. Subsize rectangular specimens were prepared according to ASTM Standard B557M [7]. The gauge length and the width of the specimens were 25 mm and 6 mm, respectively. The thickness, however, was different from each step. The cross-section areas were measured after each specimen surface was polished in order to avoid stress concentration.

After preparation, the specimens were tested at ambient temperature on an Instron 8562 universal testing machine equipped with a computer data acquisition system. The output data (displacement and tensile load) were analyzed. The tensile properties, including ultimate tensile strength (UTS), 0.2% yield strength (YS), and elongation to failure ($A$) were obtained for each step thickness.

Since it is very difficult to insert temperature sensor into the step casting for real-time measurement, numerical simulation (Magmasoft®) was employed to determine the cooling (solidification) rates (CR) of each step. Equation (1) was used to calculate the cooling rate based on the cooling curves predicted from the simulation:

$$\mathrm{CR} = \frac{T_\mathrm{l} - T_\mathrm{s}}{\Delta t} \tag{1}$$

where $T_\mathrm{l}$ and $T_s$ are the liquidus (619 ℃) and solidus (433 ℃) temperatures of AM60, respectively, $\Delta t$ is the elapsed time between $T_\mathrm{l}$ and $T_s$.

Porosity was evaluated via density measurement. Following the measurement of specimen weight in air and distilled water, the actual density ($D_\mathrm{a}$) of each specimen was determined using Archimedes principle based on ASTM Standard D3800:

$$D_\mathrm{a} = \frac{W_\mathrm{a} D_\mathrm{w}}{W_\mathrm{a} - W_\mathrm{w}} \tag{2}$$

where $W_\mathrm{a}$ and $W_\mathrm{w}$ are the weight of the specimen in air and in water, respectively, and $D_\mathrm{w}$ is the density of water. The porosity of each specimen was calculated by the following equation (ASTM Standard C948):

$$\%\mathrm{Porosity} = \frac{D_\mathrm{t} - D_\mathrm{a}}{D_\mathrm{t}} \times 100\% \tag{3}$$

where $D_\mathrm{t}$ is the theoretical density of the alloy AM60, which is 1.77 g·cm$^{-3}$.

## 2 Results and discussion

### 2.1 Solidification and microstructure

Figure 1 shows the typical cooling curves of squeeze cast AM60 with thicknesses of 6, 10 and 20 mm which were computed from numerical simulation. It took 65 s and 28.4 s for the sections of 20 and 10 mm, but only 15.2 s for the 6 mm section to cool from liquidus (615 ℃) to solidus (433 ℃). Thus the cooling rate for the 6 mm section is 11.9 ℃·s$^{-1}$, almost two and four times higher than those of the 10 and 20 mm sections which are 6.4 ℃·s$^{-1}$ and 2.8 ℃·s$^{-1}$, respectively as given in Fig. 2. The relationship between the cooling rate and grain structure has been studied in many papers, which states that the higher the cooling rate, the finer the grain structure [7-10].

Figure 3 presents the results of solidification sequences of the step squeeze casting of AM60, predicted by simulation. Figures 3(a) through (d) illustrate the casting solidified by 20%, 40%, 60% and 80%, respectively. It can be clearly seen that the thin section solidifies much faster than the thick part as the

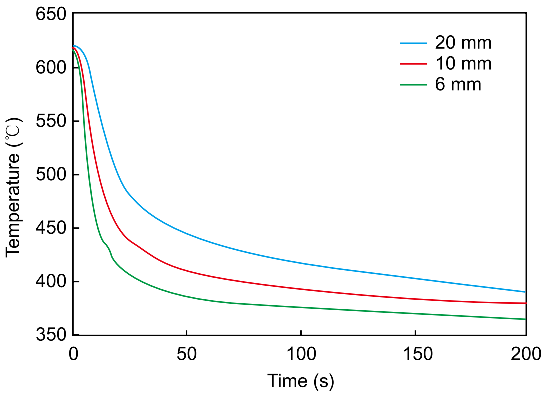

**Fig. 1: Cooling curves of samples with 6, 10 and 20 mm thick sections**

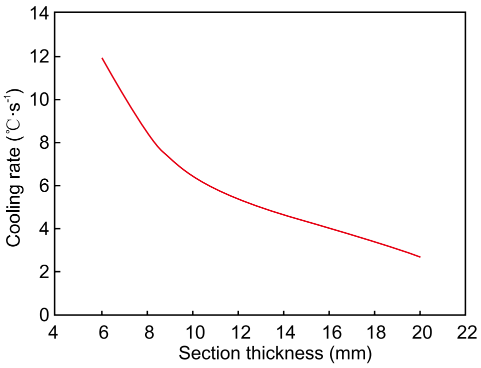

**Fig. 2: Cooling rate vs. section thicknesses**

temperature in the thin section drop more rapidly. The last solidification location ended at the center of the cylindrical gate with a diameter of 100 mm. Consequently, as shown in Fig. 2, the cooling or solidification rate of the thin section is much higher than the thick part, which has a great influence on the grain size as well as the mechanical properties of the casting.

Figure 4 shows optical micrographs taken from the squeeze cast AM60 specimens with the section thicknesses of 6, 10 and 20 mm, respectively. The average grain size increases from 16 μm for 6 mm specimen to 80 μm for 20 mm specimen. The greater total thermal energy in the thicker section of liquid metal requires more time for removal during solidification process since the thermal conductivity and the temperature of the mold are the same for all sections. As a result, the longer the time spends at the solidification temperature between the liquidus (615 ℃) and solidus (433 ℃) as illustrated in Fig. 2, the larger the grains develop. In other words, the thicker section in the same mold experiences a slower cooling rate and results in a coarser grain structure as shown in Fig. 4.

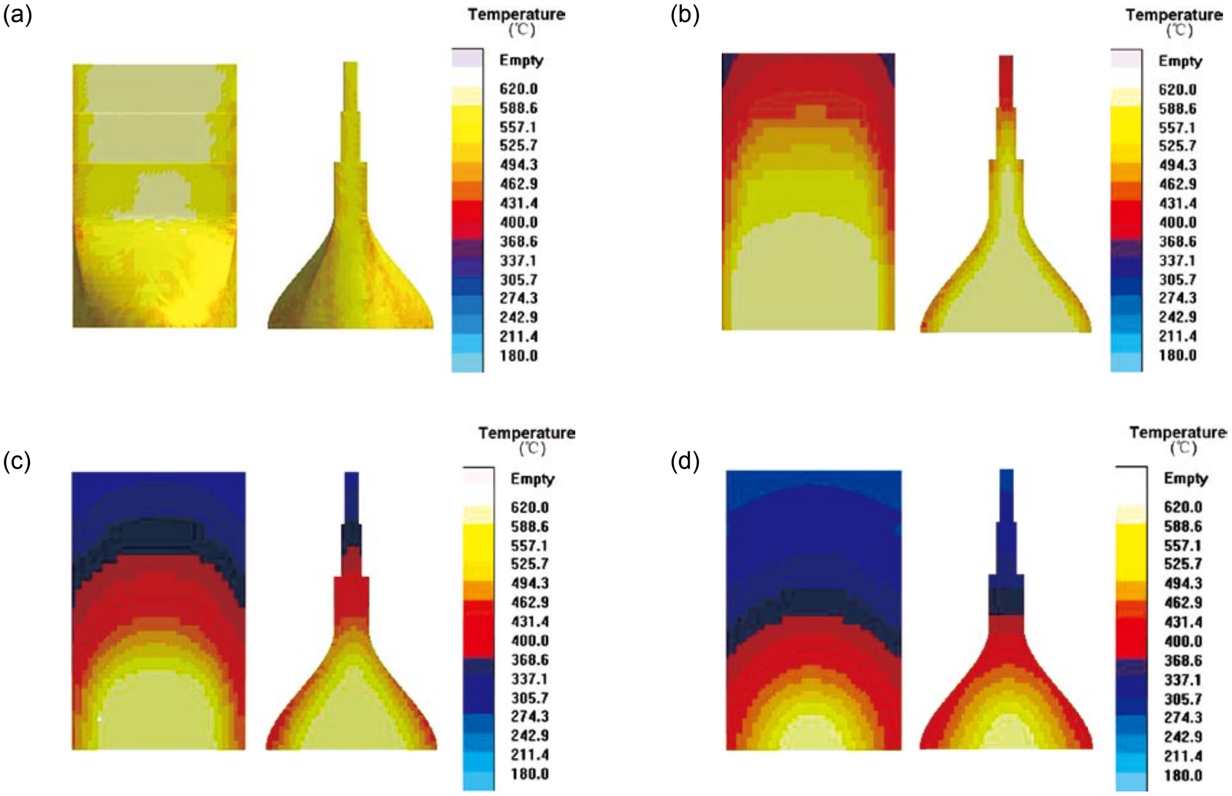

**Fig. 3: Simulation on solidification behaviour of AM60 step casting: (a) 20%, (b) 40%, (c) 60%, and (d) 80% solidified**

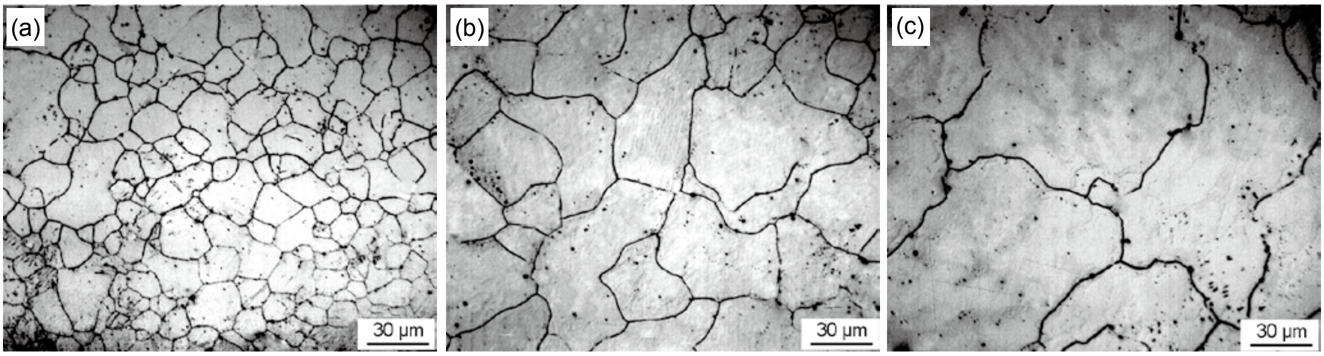

**Fig. 4: Optical micrograph showing grain size of specimens with 6 mm (a), 10 mm (b) and 20 mm (c) section thickness**

## 2.2 Porosity evaluation

The results of the optical microscopy examination are shown in Fig. 5. It can be concluded from Fig. 5(a) that the 6 mm sample contains almost no pore. However, pores can be easily spotted in the sample with section thickness of 20 mm, as indicated in Fig. 3(b).

Figure 6 presents the percentage of the porosity of squeeze cast AM60 with section thicknesses of 6, 10 and 20 mm, based on density measurement. In comparison with the thicker samples (0.7% for 10 mm and 1.3% for 20 mm), the porosity level of the sample with section thickness of 6 mm is significantly low which is only 0.2%. The considerably low porosity level of the 6 mm sample should result from the high cooling rate. The previous study on numerical simulation of solidification of the step casting suggests the long solidification time should be responsible for the high level of porosity in the squeeze casting with thick cross-sections [10].

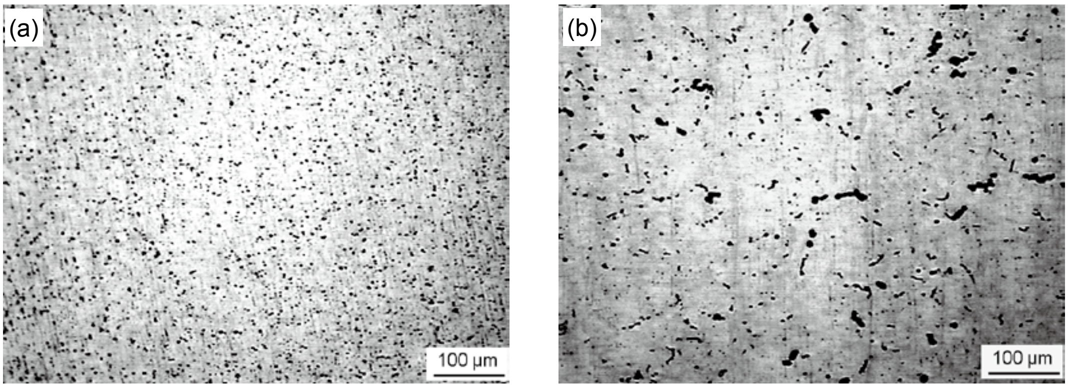

**Fig. 5: Optical micrographs of squeeze cast AM60 with section thickness of 6 mm (a) and 20 mm (b)**

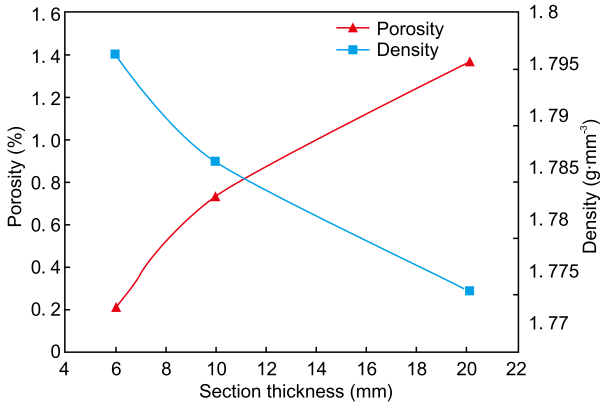

**Fig. 6: Porosity level and density vs. section thickness**

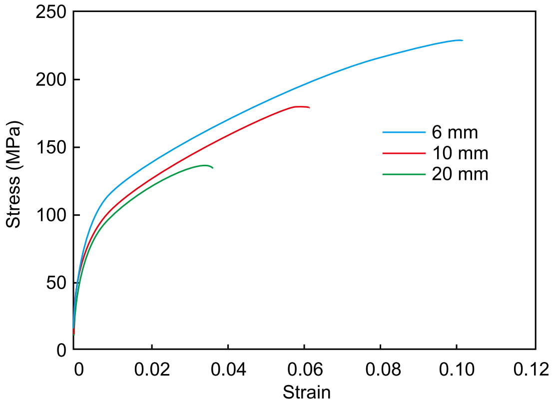

**Fig. 7: Engineering stress-strain curve of squeeze cast AM60 alloy**

## 2.3 Tensile properties

Figure 7 shows representative stress and strain curves for each step thickness of the squeeze cast AM60 alloy. For all the three section thicknesses of specimens, the curves show that the alloy deforms elastically first under tensile loading. After reaches the yield point, the alloy starts to deform plastically. The effect of section thickness on tensile properties of squeeze cast AM60 is summarized in Table 2.

Figure 8 shows the variation of ultimate tensile strength, yield strength and elongation with section thickness. It is obvious that the specimen with the thin section (6 mm) has higher ultimate tensile strength, yield strength and elongation than the thick specimen (10 mm or 20 mm). It shows that a decrease in section thickness from 20 to 6 mm enhances the elongation with a 176% increment from 3.69% (20 mm) to 10.19% (6 mm). Also, there are 43% and 67% increases in yield strength and ultimate tensile strength over the 20 mm thickness, respectively.

**Table 2: Variation of tensile properties with section thickness**

| Thickness (mm) | YS (MPa) | UTS (MPa) | *A* (%) |
|---|---|---|---|
| 6 | 96 | 229.89 | 10.19 |
| 10 | 74 | 181.04 | 6.52 |
| 20 | 67 | 137.68 | 3.69 |

The variation on grain size from one section to another has a large influence on the mechanical properties. It appears for the most prominent enhancement of the mechanical properties: strength. As the grain size decreases, the strength increases significantly. The porosity level seems directly related to the ductility of the squeeze cast AM60. As the porosity level drops from 1.3% for the 20 mm to 0.2% for the 6 mm section, the elongation of the alloy increases from 3.69% to 10.19%. As such, the improvement in the tensile properties should be attributed to the low porosity level and fine cell structure of thin specimen. In other words, the low strength and poor

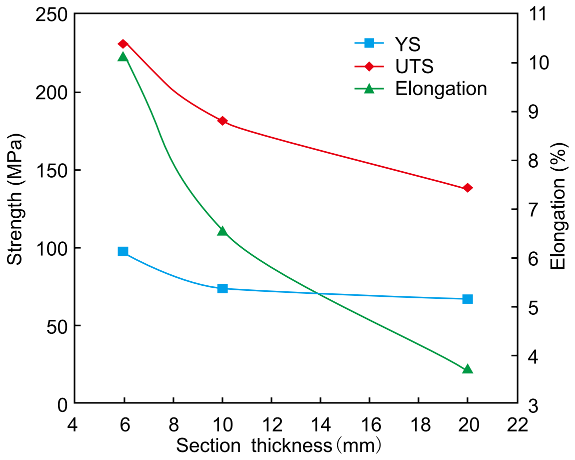

**Fig. 8: Ultimate tensile strength (UTS), yield strength (YS) and elongation vs. section thickness**

elongation of the thick specimen should be resulted from coarse microstructure and high porosity level.

### 2.4 Fracture behaviour

Fracture surfaces of the tensile specimens were examined via SEM. Fractographs in Fig. 9 exemplifies the range in fracture behaviour among 6 mm, 10 mm and 20 mm thick specimens. The SEM fractography analysis shows that the fracture behaviour of squeeze cast AM60 is influenced by section thickness. The fracture tends to transit from ductile to brittle as the section thickness increases.

Figure 9(a) illustrates a ductile fracture surface of 6 mm thick specimen which is characterized by the presence of deep dimples and dramatic height variations resulting from the elongated nature of the surface. The dimples are formed by the extensive deformation of individual crater walls. In this mechanism, the sample fails by microvoid coalescence under tensile stress. The microvoids nucleate at the areas of localized high plastic deformation which associates with the second phase particles and grain boundaries. Eventually, a continuous fracture surface forms as the microvoids grow. A considerable amount of energy is consumed of the formation of microvoids and finally leading to creation of cracks. Figure 9 (b) shows a fracture behaviour that tends to become more brittle comparing with Fig. 9(a). The characteristic feature of cleavage fracture, flat facets, is appeared in Figs. 9(b) and (c). Figure 9(c) is considered as primary brittle fracture. The cracks move through the grain along a number of parallel planes, which forms a series of plateau-like flat surfaces as a result of the crystallographic shearing effect. In general, the SEM fractography results are in agreement with the results from the tensile test data (shown in Table 2), that is the elongation or ductility increases as the sample thickness decreases.

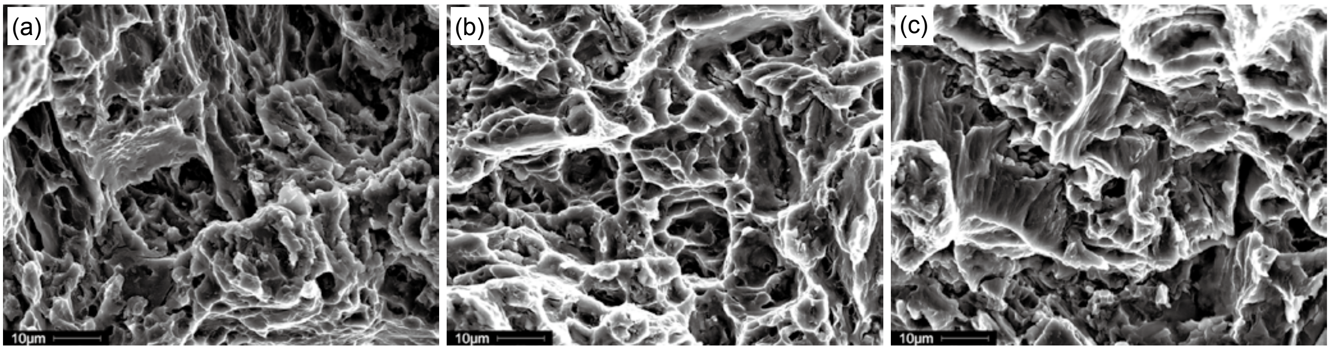

**Fig. 9: SEM fractographs of 6 mm (a), 10 mm (b), 20 mm (c) thick squeeze cast AM60 samples**

## 3 Summary

Step squeeze castings of magnesium alloy AM60 with different section thicknesses of 6, 10 and 20 mm were cast under an applied pressure of 30 MPa. The numerical simulation predicted that the solidification rate of the squeeze cast AM60 alloy increased from 2.8 ℃·s$^{-1}$ to 11.9 ℃·s$^{-1}$ with the decreasing section thicknesses from 20 mm to 6 mm, which implied fine microstructure in the thin section. The tensile properties of the alloy are influenced by the section thickness. The significant increases in elongation (176%), ultimate tensile strength (67%) and yield strength (43%) of the 6 mm step over the 20 mm section are achieved. The dependence of tensile properties on the section thickness should be attributed to the variation of solidification rate and the resulted microstructure of the squeeze cast AM60 alloy. The microstructure features of the 6, 10 and 20 mm specimens were studied via optical metallography and SEM analysis. The section thickness has significant influence on the porosity level of the squeeze cast samples. As the section thickness increases, the porosity level rises and consequently reduces the tensile properties. The observation via SEM fractography illustrates that the fracture behaviour is affected by the section thickness. The fracture of AM60 tends to transit from ductile to brittle as the section thickness increases.

## Acknowledgements

The authors would like to thank the Natural Sciences and Engineering Research Council of Canada, and University of Windsor for supporting this work.

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*The paper was presented at the 11th Asian Foundry Congress, Guangzhou China 2011, and republished in China Foundry with the authors' kind permission.*