

Predicting Stress vs. Strain Behaviors of Thin-Walled High Pressure Die Cast Magnesium Alloy with Actual Pore Distribution

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ABSTRACT

In this paper, a three-dimensional (3D) microstructure-based finite element modeling method (i.e., extrinsic modeling method) is developed, which can be used in examining the effects of porosity on the ductility/fracture of Mg castings. For this purpose, AM60 Mg tensile samples were generated under high-pressure die-casting in a specially-designed mold. Before the tensile test, the samples were CT-scanned to obtain the pore distributions within the samples. 3D microstructure-based finite element models were then developed based on the obtained actual pore distributions of the gauge area. The input properties for the matrix material were determined by fitting the simulation result to the experimental result of a selected sample, and then used for all the other samples' simulation. The results show that the ductility and fracture locations predicted from simulations agree well with the experimental results. This indicates that the developed 3D extrinsic modeling method may be used to examine the influence of various aspects of pore sizes/distributions as well as intrinsic properties (i.e., matrix properties) on the ductility/fracture of Mg castings.

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INTRODUCTION

Magnesium castings have found increasing applications in lightweight vehicles because magnesium and its alloys are the lightest metallic structure materials. However, a critical technical hurdle hindering the wider applications of magnesium castings in vehicle applications is its limited ductility. Various microstructural features such as properties and distributions of porosity, brittle eutectic phases and grain size can influence the ductility of Mg alloys. However, all these microstructure-level features vary from specific alloy to alloy, different casting processes, and different locations on a single casting [1, 2]. Although some commercial casting softwares or material models are available for the researches of magnesium castings, their predictive capability typically stops short of predicting the location dependent stress-strain behavior, particularly ductility.

The factors limiting the ductility of Mg castings can generally be categorized into two types: intrinsic (i.e., the phase composition, grain size, morphology, volume fraction and mechanical properties of the α -Mg matrix and the eutectic β phase, etc.) and extrinsic (i.e., porosity, segregation, incomplete fill, hot tear, cold shut, etc.). The specific alloy design and casting process parameters determine both factors which in turn influence the ductility of the final cast. The authors have adopted two complementary modeling approaches (i.e., intrinsic/extrinsic modeling) in investigating the influence of various microstructure-level features on the strength/ductility of Mg castings [3,4,5]. Here, the bulk performance predicted from the lower

length-scale intrinsic modeling can be used as input properties for the matrix material in the larger length-scale extrinsic modeling. In this sense, these approaches can be an example of integrated computational materials engineering (ICME).

This paper is focused on the extrinsic modeling which investigates the effects of porosity. In our previous extrinsic modeling works [4,5], synthetic microstructure-based two-/three-dimensional (2D/3D) finite element models generated based on the characteristic inputs (e.g., quantified pore size, volume fraction) were adopted for examining the qualitative effects of various aspects of porosity, but without the experimental validation. The purpose of the current study is to develop/validate a new extrinsic modeling method where the actual microstructure-based 3D finite element models are generated based on the actual pore distribution data obtained from CT-scan of the tensile samples. For this, as-cast AM60 tensile samples generated from a special die [6] were used in the current modeling work. The modeling results were also validated against the experimental results in terms of the ductility and fracture location.

EXPERIMENTS

Figure 1 shows a special metal die used to produce several different sizes of round and flat tensile samples for examining the effects of cast skin on the mechanical properties of high pressure die casting (HPDC) AM60 Mg alloy [6]. The as-cast tensile samples, designated

F3 in the figure, were used for the modeling work in the current study. Note that F3 samples were generated according to the ASTM E8 subsize specimen with 25.4mm gauge length and 2.5mm thickness as depicted in Figure 1. The chemical compositions of AM60 Mg alloy are also listed in Table 1. The details of the HPDC process using the die shown in Figure 1 are reported in Forsmark et al. [6].

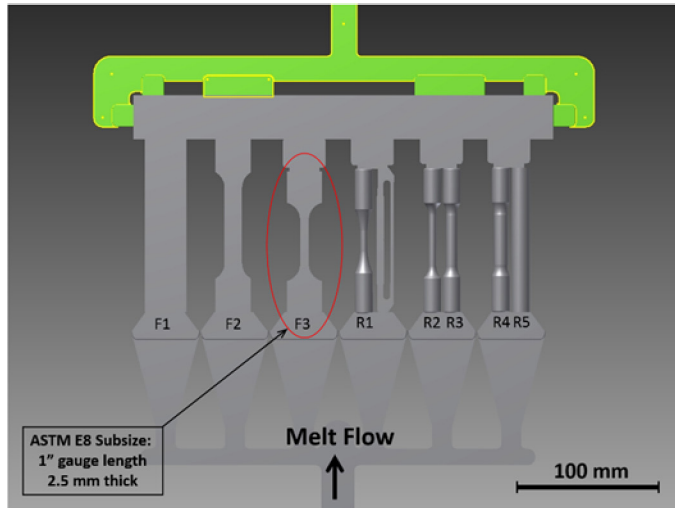


Figure 1. (a) Die geometry for casting round and flat tensile samples [6].

Quasi-static tensile tests (at 2.0 mm/min) were performed to obtain the stress-strain curves of F3 tensile sample. Table 3 lists the mechanical properties measured from eleven F3 samples, generated based on the same casting condition, and Figure 2 shows their stress-strain curves. Here, the colored-solid lines simply represent the stress-strain curves of the four samples selected for the modeling work in this study (i.e., #2, 7, 15, 19). As shown in the figure, the samples show similar yield strength levels and hardening rates during the initial loading process except for one sample (i.e., #19). This indicates that, in general, the initial strength level is not noticeably influenced by the microstructure-level features. However, their fracture strains and, consequently, their fracture strengths are quite different from each other. It was found from various studies that this difference in ductility can be attributed to the different microstructure-level features, mainly, pore size, distribution and volume fraction. Note that the porosity features may be quite different even among the samples with the same casting/preparation condition [7]. These features may also be different from local location to local location within a tensile sample.

Table 1. Chemical compositions of AM60 castings (wt.%).[6]

Al	Mn	Si	Cu	Zn	Ni	Fe
6.0	0.29	0.02	0.0012	0.04	0.0001	0.0012

Table 2. The mechanical properties of the AM60 Mg alloy (F3 as-cast samples).

YS (0.2% offset) (MPa)	98 ± 6
UTS (MPa)	207 ± 22
Elongation at failure (%)	7.2 ± 2.1

In order to examine the porosity effects and establish an extrinsic modeling method, CT scans with resolution of $\sim 19 \mu\text{m}$ were performed on the samples prior to the tensile testing. 3D pore distribution features within the tensile samples were obtained by scanning their gauge areas. For example, Figures 3(a) and 3(b) show the cross-section CT images of the four selected samples in W - L plane view and T - W plane view, respectively. Here, L , W , T represent the length, width, thickness, respectively. The casting marks remained intact to retain the as-cast condition of the F3 samples as shown in Figure 3(b).

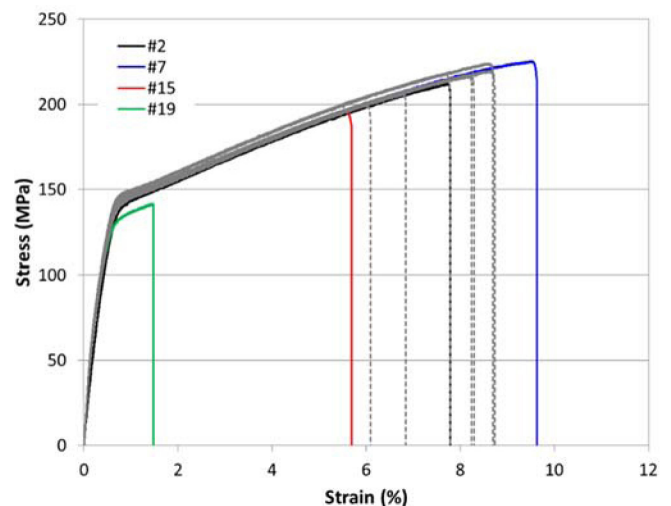


Figure 2. Stress-strain curves of F3 samples. (Four F3 samples were selected for modeling work.)

It is noticed that the ductility ranking of the four samples can be rather anticipated from the cross-section CT images shown in Figure 3. For example, Sample #15 appears to have relatively high pore volume fraction which led to a lower ductility compared to those of Samples #2 and #7. Note that, for Sample #19, many crack-shaped large pores were observed all the way through the gauge length as shown in Figure 3. These large-sized pores are believed to be the source for the lower yield strength (due to the reduction of effective load-carrying cross-sectional area) and the very low ductility of the sample.

MODELING

Microstructure-based finite element modeling method has been adopted in our intrinsic/extrinsic modeling approaches for the study of cast Mg alloy. In intrinsic modeling approaches, the intrinsic microstructural features of cast Mg alloy (i.e., grain size, morphology, volume fraction and mechanical properties of the α -Mg matrix and the eutectic β phase, etc.) were explicitly meshed out in the model, and their influence on the bulk performance was investigated [3]. Similarly, the pore distributions are explicitly modeled and their influence on the material performance is examined in the extrinsic modeling approach [4,5]. In this study, as an extrinsic modeling method, the images obtained from CT scan of the four selected F3 samples were used to generate 3D finite element models representing their gauge areas. The model generations based on CT data and the material property determination are explained in this section. The commercial finite element code ABAQUS/Explicit [8] was used for the analyses in this study.

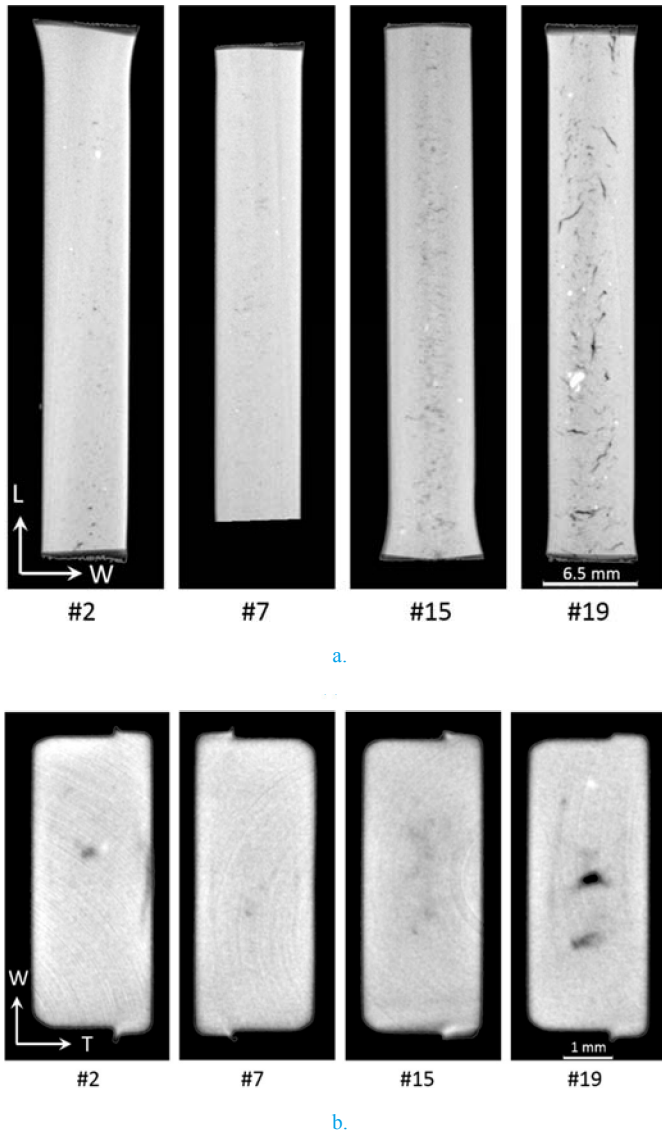


Figure 3. Computerized X-ray tomography showing cross-sections of the selected samples. (a) *W-L* plane view and (b) *T-W* plane view.

Microstructure-Based Finite Element Models

In the current extrinsic modeling method, some bright areas observed in the CT images (i.e., hard particles in the material) are not considered in the modeling, and only dark areas are considered and modeled as the pores. Figure 4 shows a schematics showing 3D finite element model generation based on the CT data. Brief explanations on each step of model generation are given below.

1. A portion of gauge area for the extrinsic modeling work is first determined.
2. The stack of black and white (B/W) cross-section images, representing the pore distributions, are generated from CT images based on a simple thresholding method (i.e., grayscale threshold). The original high resolution (e.g., $\sim 19 \mu\text{m}$ in this case) is maintained during the thresholding step.
3. In order to develop a 3D finite element model with reasonable computational size, the stack of high resolution B/W images are converted to the stack of gray-scale images using coarsening/

averaging process based on a scale factor. For example, in Figure 4, the gray-scale cross-section image (33×78 voxels) is the resultant after combining and averaging the four consecutive high-resolution cross-section images (130×310 voxels) shown in the figure.

4. The stack of coarsened gray-color images are converted to the stack of new coarsened B/W images. A thresholding criterion may be needed during this step. For example, pore volume fraction in the gauge area, if measured, may be used as a thresholding criterion. As shown in Figure 4, small-sized pores observed in the original high-resolution B/W images may disappear in the new coarsened B/W images, depending on the adopted thresholding criterion.
5. 3D finite element model is finally generated based on the stack of new coarsened B/W images using cube-shaped solid element (C3D8R). Each voxel of the new B/W images corresponds to one element of the 3D model. Figure 4 shows an example of 3D finite element model generated based on a stack of CT images, which shows pore distributions. In the model, extra solid regions (i.e., no pore region) are attached to both ends of modeled region in order to represent the grip region of tensile samples.

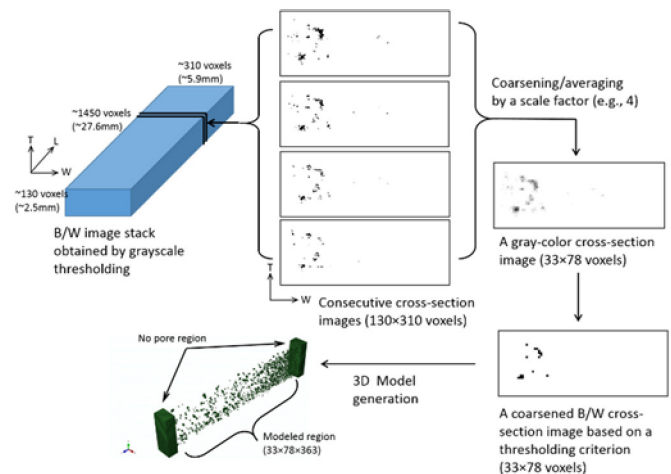


Figure 4. Schematics of 3D finite element model generation based on CT images.

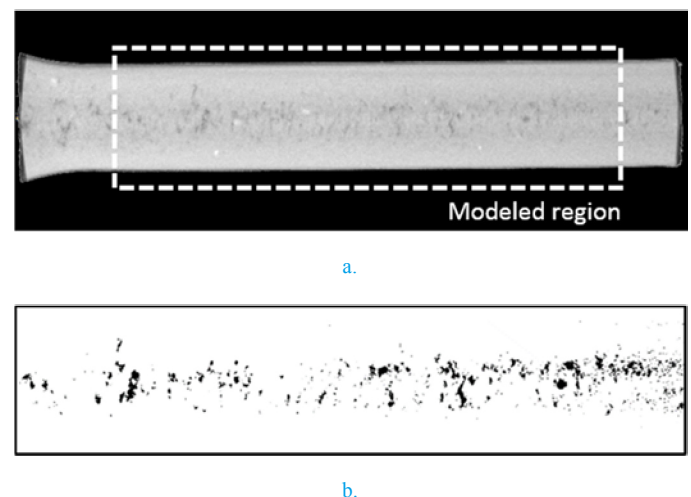


Figure 5. Generation of 3D finite element model for an as-cast F3 sample (#15). (a) A cross-section image from CT scan, (b) B/W image of the selected gauge area and (c) generated 3D model.