Effect of Pores on Tensile Fracture of Die-cast AlSiMgMn alloys with 3D X-ray μ-CT and FE Simulation

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Abstract. In this study, the pores in die-cast AlSiMgMn alloys were inspected and reconstructed with high resolution three-dimensional (3D) X-ray micro computed tomography (μ-CT) technique. Finite element (FE) meshes were built with consideration of the pore actual morphorloges from the CT inspection. Based on dutile damage model, the FE simulation of tensile fracture of the alloys was carried out. The simulation results were compared and verified with the tensile of in-situ scanning electron microscopy (SEM). The two results are agreement in the main crack path and pores on the fracture. With the pore-scale simulation, the effects of pore characteristics on the stress distributions and crack initiation and growth during the tensile were analyzed. It was found that the pores of lower sphericity and larger project area in tensile axis direction are prone to form microcracks and promote main crack deflection. The results also show that aggregation of brittle alpha-Fe intermetallics of the alloys also has important influence on the main crack propagation.

1. Introduction

Vehicle lightweighting is a key pursuit of automotive industries and drives carmakers to use more aluminum castings for replacing heavy iron based parts [1]. Die casting process is particularly preferred by engineers to produce aluminum components for automotive applications since it has the advantages of good surface quality, excellent dimensional precision and high producing efficiency. However, gases are inevitably entrapped in the molten alloys during high speed mold filling process, resulting in undesired porosity defects [2] which reduce the effective load-bearing areas and cause local stress concentration [3-5].

These days, 3D X-ray CT has been increasingly used to investigate the spatial characteristics of pores (e.g. pore volume, surface area, sphericity and locations) and their roles in material failure [6-8]. Weck et al. [9] applied X-ray to assess the accuracy of existing models in capturing the void growth and coalescence in metals. Nicoletto et al. [10] numerically simulated the stress concentration around an X-ray reconstructed pores in AlSi7Mg casting under push-pull testing. Our previous work on quasi-static stress concentrations around pores under fatigue load also shows that pores near casting surfaces could cause more stress concentration [11]. However, as our known simulation on dynamic fracture of die-cast Al alloys with consideration of micro-scale pore characteristics has not been reported.

In this study, the 3D pores in die-cast AlSiMnMg alloys, which with high strength and ductility [12], was reconstructed by X-ray CT. FE analysis of tensile test was then performed on the reconstructed 3D structure. The predicted crack path was compared with the experimental result identified by scanning
electron microscopy (SEM). The effects of pores on stress distribution and crack propagation were discussed.

2. Experiment and simulation

2.1 Materials and experiment

The material used in this study was die-cast AlSiMnMg alloys. The chemical compositions of this alloy were measured by ICP ARL4460 including: 10.10%Si, 0.075%Fe, 0.62%Mn, 0.12%Mg, 0.012%Sr. The castings are of 2300×200×25 mm, and were fabricated by 2000 tons cold chamber die casting machine. In the die casting process, the pouring and die temperatures are 680 and 200 °C, respectively. To investigate the effect of pores on crack propagation, the tensile samples (figure 1) were directly cut from practical pedal die-castings. The gauge length, width and thickness of the sample are 16, 2.5 and 1.3 mm respectively. Tensile tests were carried out at room temperature with the velocity at 1 μm/s. After the tensile, the fracture morphology and crack path in the sample surface were observed by SEM (Nova Nano 430).

In order to characterize the internal pores, the region near the notch as indicated by the dashed rectangle in figure 1 (about 4 mm along the tensile direction) was inspected by the X-ray CT instrument nanoVoxel-2000 (Sanying Precision Instruments Co.,Ltd). During the inspection, the voltage and current of the X-ray tube were 120 kV and 80 μA, respectively. Though the instrument has maximum resolution of 0.5 μm, to obtain the pores in the whole region the inspection resolution in the experiment was 3.88 μm. Then the CT data were imported into Volume Graphic (VG) Studio MAX 2.2 software to carry out pore 3D reconstruction, with which the volume, sphericity and spatial distribution of pores were determined.

![Figure 1. Shape and dimension of the in-situ tensile samples.](image1)

![Figure 2. Reconstructed of micropores in the die-cast AlSiMgMn alloys.](image2)

2.2 FE simulation

To simulate the tensile fracture of the die-cast AlSiMgMn alloys, the ductile damage model was used since the alloy is of good ductility. It is usually used to predict the onset of damage due to nucleation, growth, and coalescence of voids in ductile metals [13]. In the model equivalent plastic strain at the onset of damage, $\varepsilon_{pl}^d$, is a function of stress triaxiality ($\eta$) and strain rate ($\dot{\varepsilon}_{pl}$). In the simulation, the stress triaxiality is defined as

$$\eta = \frac{-p}{q}$$

where, $p$ is the pressure stress and $q$ is the Mises equivalent.

The criteria for material damage is given by

$$\omega_d = \int \frac{\sigma_{pl}}{\varepsilon_{pl}^d (\eta, \dot{\varepsilon}_{pl})} = 1$$

where, $\omega_d$ is a state variable, and increases with plastic deformation, the increment of $\Delta \omega_d$ during the calculation process was defined by
The Abaqus software was used as the simulation platform, and material properties was set as isotropic hardening, which based on the von Mises type elastoplastic constitutive law. According to the tensile test conditions, the fracture strain, stress triaxial and strain rate are set to 0.07, 0.33, and 6.25×10⁻⁵ respectively. And a stress-strain curve of experiment tensile process was input into the Abaqus software as parameters of materials properties. The AlSiMgMn alloy density was set to 2.67 g/cm³, and young’s modulus and poisson’s ratio were 76 GPa and 0.33 respectively.

3. Results and discussion

3.1 FE meshing with pore 3D characteristics

Figure 2 exhibits the reconstructed pores in the inspection domain. According to the resolution (3.88 μm) of inspection, pores with the volume larger than 7×10⁶ mm³ could be precisely detected. The total pores number is 73 and average pore volume is 6.5×10⁻⁵ mm³. Eleven of them have the volume more than 1×10⁴ mm³, among which the biggest one is of 1.118×10⁻³ mm³.

To simulate effect of the pores on tensile fracture, the FE model with the pores must be established. After the CT inspection, the data of serial XY sections were imported into the Mimics software to generate the triangular surface meshes of specimen. As well known, large pores in the body and pores adjacent to the surfaces of the alloy were more detrimental compared to other pores. Therefore, in our simulation the large volume pores (bigger than 1×10⁻⁴ mm³) and subsurface pores were kept in the computational model and relatively smaller pores were removed to improve calculation efficiency and prevent numerical diffusion in FE calculation. The ratio of height to base (H/B) in the triangle was controlled no more than 0.4 to improve grid quality, and for improving FE iteration the minimum and maximum sizes of the triangle element were set as 3 and 100 μm respectively. The surface meshes were exported as input file of Abaqus. Then, volumetric tetrahedral meshes were built form the triangular meshes in the Abaqus software as shown in figure 3a. Due to the complex details, the pores and notch part were set with smaller and denser meshes. Figure 3b shows the FE meshes for a pore. To calculate the fracture under monotonic loading of the room temperature, one side (top) was set to fixed boundary condition, while the opposite surface (bottom) was considered uniform motion at the velocity of 1 μm/s as shown in figure 3a.

![Figure 3. 3D FE enmeshment of pores and boundary condition set-up.](image)

Figure 4. Distribution of pores on FE model: (a) view from the Z axis, (b) view from the Y axis.

Figure 4a and 4b show the pore distributions from Z and Y axis directions. For convenience of description later, the pores were numbered according to their volumes. Table 1 lists the details of pore characteristics in the calculation domain. The pore P1-11 are of bigger volume, among which the P1,P3, P4, and P6 are near the boundary. The pore P19, P21, and P22 are also close to the surface but they have small volumes. In table 1, PZ means the projected area of a pore in the tensile direction and Z is the distance of the pore to the minimum cross section. It is found from table 1 that the pores with larger
volume usually have higher PZ values. According to the Z values, the pore P1, P2, P4, P6, P10, P11, P12, P14 and P18 are far away from the section, and occasionally the pore P7 and P23 are in the section.

Table 1. Characteristics of pores in the FE model

| Pore | Volume (10^6 x mm^3) | Sphericity | PZ (10^4 xmm^2) | Z (mm) | Pores | Volume (10^6 x mm^3) | Sphericity | PZ (10^4 xmm^2) | Z (mm) |
|------|----------------------|------------|-----------------|--------|-------|----------------------|------------|-----------------|--------|
| P1   | 1118                 | 0.47       | 133             | 0.33   | P13   | 61                   | 0.45       | 20              | 0.18   |
| P2   | 987                  | 0.46       | 158             | 0.34   | P14   | 61                   | 0.54       | 16              | 0.44   |
| P3   | 179                  | 0.32       | 45              | 0.19   | P15   | 57                   | 0.47       | 23              | 0.17   |
| P4   | 170                  | 0.48       | 38              | 0.25   | P16   | 56                   | 0.46       | 28              | 0.16   |
| P5   | 144                  | 0.36       | 46              | 0.14   | P17   | 53                   | 0.65       | 18              | 0.21   |
| P6   | 129                  | 0.64       | 31              | 0.41   | P18   | 50                   | 0.42       | 22              | 0.24   |
| P7   | 126                  | 0.46       | 40              | 0      | P19   | 41                   | 0.6        | 17              | 0.11   |
| P8   | 119                  | 0.6        | 30              | 0.11   | P20   | 33                   | 0.42       | 13              | 0.25   |
| P9   | 114                  | 0.38       | 50              | 0.10   | P21   | 32                   | 0.58       | 16              | 0.06   |
| P10  | 112                  | 0.51       | 33              | 0.34   | P22   | 31                   | 0.5        | 13              | 0.08   |
| P11  | 104                  | 0.58       | 32              | 0.31   | P23   | 30                   | 0.49       | 13              | 0      |
| P12  | 93                   | 0.62       | 26              | 0.43   | P24   | 18                   | 0.48       | 10              | 0.003  |

3.2 Characteristics of fracture

Figure 5 displays the fracture observed from the front surface of the tensile specimen by SEM, and figure 5b gives the simulated fracture using the meshes generated from the CT image data. It can be seen that the simulated fracture path resembles the experimental result, indicating a good agreement between these two results. The morphology of the fracture surface is shown in figure 5c. Many pores were clearly observed on the fracture surface, confirming effect of pores on cracks. According to figure 4a, the pores P1, P4 and P21 are near the sample surface. They caused stress concentration according to our former calculation [11] hence inducing the fracture. According to the Z values in table 1, the pores P5, P7, P8, P9, P13, P17, P19 and P21 are near the minimum section. Due to the notch, the decreased area of the minimum section increased the stress. In result, even though some of them are with smaller volume, they still affected the crack propagation. For example, the pore P21 has quite small volume and high sphericity (table 1). But it is found on the fracture due to near of the surface (figure 4a) and the minimum section (0.06 Z value) that pores near the boundary and minimum section are easy to nucleation cracks. Compared to the experiment result, the simulation crack not only go through all pores in the fracture but also go through the pores P13 and P19. Other pores that with small volumes or far away from notch (the value of Z larger than 0.25 mm) did not appeared in the fracture surface.

Figure 5. Comparison of the experiment and simulation: (a) experimental crack, (b) simulated crack, (c) pores on the fracture, (d) pores on the simulated fracture.

The simulation results show that the crack went through the pore P13 and P19. However, these two pores were not experimentally observed on the fracture surface, as shown in figure 5c. To further investigate the disagreement, the regions of fracture surface with similar projected location of two pores along the tensile direction were analyzed with SEM, which is shown in figure 6. It is obvious in the figure that the continuously distributed α-Fe intermetallics i.e Al15(Fe,Mn)3Si2 exist on the fracture.
surface as indicated by the arrows. The study on the similar alloys by Dominik [14] showed that the α-sludge particles and α-Fe intermetallic tended to initialize cracks due to their low plasticity. Therefore in the regions the crack path was controlled by these clustered intermetallics, leading to the simulation disagreement in these regions.

**Figure 6.** The difference between simulated and experimental results: (a) region of pore P13, (b) region of pore P19, (c) EDS analysis results of α-Fe phase.

### 3.3 Effect of pore on crack nucleation

Many researches have shown that the morphology of pore has significant effects on crack initiation. In the simulation, micro-cracks originated from the pores were found before the main crack passing through. Figure 7 plotted the times of microcrack initialization against the PZ values of pores, i.e. the projected area of a pore on the horizontal plane. A larger PZ value represents a larger reduction of the loading-bearing area in the specimen during the tensile test. Generally the initiation time of micro-crack decreases as the PZ value increases for all pores except the pore P4 and P9. Figure 8 shows the stress distribution and micro-crack formation around the pore after 71 s and 110 s. According to table 1, the sphericity of pore P4 is 0.48 (a shape close to gas pore) and the Z value (the distance to the plane of the minimum cross section) is 0.25 mm. As a result, the stress level of pore was lower at 71 s as shown in figure 8a and the crack nucleation on it is later (figure 8b). On the contrary, the pore P9 has a smaller sphericity of 0.38 and a Z value of 0.1, i.e. relatively closer to the minimum cross section. Therefore, larger stresses were found around the pore and the micro-crack nucleated at early time of 71 s as displayed in figure 8c. At 110 s, three micro-cracks formed on the pore, see figure 8d. The simulation results indicate that pores with lower sphericity and closer to the minimum sections cause more serious local stress concentration and accelerate the formation of micro-cracks nearby.

**Figure 7.** Times of micro-crack initialization on pores with different projection areas

**Figure 8.** Stress distribution and crack initialization around: (a) P4 at 71s, (b) P4 at 110s,(c) P9 at 71s, (d) P9 at 110s

### 3.4 Stress distribution during tensile crack propagation

Figure 9 shows the stress distribution and crack formation on whole simulation domain at macroscopic level. In figure 9a, stress concentration develops at the root of the notch at the beginning of tensile test. With the increase of tension, the stress concentration near the notch proceeds to develop and leads to
the local failure by crack. As shown in figure 5b, the crack forms at the root of the notch and propagates down to the region below the minimum cross section where pores of P2, P19 and P20 are found according to the CT data in figure 4b. However, with more increase in tension, the crack turns up and moves towards the region where pores were located. This is because more pores located at the center of the minimum cross-section as shown in figure 4b, where tends to develop more serious stress concentration. At the late stage of the tensile testing, the crack propagates downward again and leads to the complete failure to the specimen, as shown in figure 9d. This downward propagation was induced by the pores of P23 and P24 which are located at the minimum cross-section in figure 4b. The above FE analysis incorporating the 3D pores gives a clear picture of the significant effect of pore distribution on the crack propagation. The crack tends to propagate towards to the region where pores are located since the more serious stress concentration would develop nearby.

![Figure 9. Mises stress distribution during tensile: (a) tensile beginning, (b) crack propagation, (c) crack expansion, (d) crack propagation in the final fracture.](image)

4. Conclusion

The X-ray CT was used to reconstruct the pores in die-cast AlSiMgMn alloy. Using the FE meshes from the X-ray data, the tensile failure process of the alloy was simulated. The simulation was compared with the experimental results. It can be summarized:

1. The simulated crack path agrees well with the experiment result. Most of the pores on the simulated fracture surface were experimentally observed. The disagreement between the simulation and experiment was caused by the brittle clustered α-Fe intermetallics.
2. The simulation reveals that the porosity defects significantly affect the crack path during casting failure process. Crack tends to propagate towards the region where pores were located.
3. The pores with lower sphericity and closer to the minimum sections cause more serious local stress concentration and therefore accelerate the formation of micro-cracks nearby.

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