An Initial Evaluation of CT Scanning for Measuring and Characterizing Porosity in Aluminum Die Castings

Itamar Brill, Branden Kappes & Stephen Midson

Colorado School of Mines, Golden CO
Introduction

• Porosity is very important in die castings
• But despite its pervasiveness
  • Little quantitative data on porosity in die castings
• Common techniques used to measure porosity
  • X-ray
  • Sectioning castings
  • Density measurements
• Linsey & Wallace, 1972
  • Between 0.5% and 4.1% porosity
    • Dependent upon processing conditions
Porosity Distribution in Die Castings

- Porosity distribution in die castings is not uniform
  - Typically located towards the center of the castings
  - Dense skin formed at the surface
    - Reported to be about 0.5 mm wide
    - Very important for leak tight castings
    - Has a significant effect on mechanical properties
X-Ray Computed Tomography (CT Scans)

- Has potential for providing quantitative data on porosity in die castings
  - Size, shape distribution
  - Help us to dramatically increase our knowledge regarding porosity in die castings
- CT scanning
  - Nondestructive 3-D imaging technique
    - Sample is rotated in front of x-ray beam
    - Volume reconstructions produced from 2-D x-rays
    - Contrast is based on differences in x-ray attenuation
CT Scanning

• Different CT scanning processes
  • X-ray tomography
    • Minimum resolution - hundreds of micro-meters
  • X-ray micro-tomography
    • Minimum resolution – less than a micro-meter
  • Neutron tomography
    • Minimum resolution - around a micro-meter
Current Study

- Used x-ray microtomography
  - Examine size and distribution of all pores in a casting
- Detect porosity larger than 50 µm
  - Pores around this size start to decrease fatigue life

Impact of pore size on fatigue life

Source: J.F. Major, Trans. AFS. 1997
Cast-to-Size Tensile Bar

- Used as-cast tensile bars for this study
  - Ideal shape for micro-CT scanning
  - Testing has shown that these tensile bars can meet NADCA handbook mechanical properties
Production of Tensile Bars

Premier die

NADCA die
Gates for Tensile Bars

- Tensile bars had different gates
  - Premier die – circular gate
  - NADCA die – semi-circular gate
  - Is there an impact of gate shape on porosity?
Samples Locations

- ~2-inch long sections from cut from the tensile bar
gage and grip
  - Grip ~ 0.375 inches (9.5 mm) diameter
  - Gage – 0.25 inches (6.4 mm) diameter
X-ray Micro-CT Measurements

- ZEISS Xradia 520 Versa microscope
  - Resolution 10.1 µm
    - Identification of pores with effective diameter of 30.3 µm
    - Quantitative shape determination of pores with effective diameter of 101 µm
Data Collected from Each Scan

• Collected for each pore
  • Volume
  • Surface area
  • Position
  • Dimensions (X,Y,Z)

• Calculated for each pore
  • Equivalent diameter (D)
  • Sphericity (Ψ)

\[
D = 2 \left( \frac{3 \sqrt[3]{V_p}}{\sqrt[3]{4\pi}} \right)
\]

\[
Ψ = \frac{\pi^{1/3} (6V_p)^{2/3}}{A_p}
\]

- \(V_p = \text{volume of pore}\)
- \(A_p = \text{surface area of pore}\)
Positions of the Pores

- Volume and surface area of pores are independent of coordination system.
- Positions of the pores are measured in relation to x-ray beam.
- Need to be translated to be located in relation to tensile bar axis.
NADCA Tensile Bar
NADCA Tensile Bar
NADCA Tensile Bar

- 64,685 pores larger than 36 µm
- Sample weight 6.1 g
- Total volume of porosity
  - 28,368,517,344 µm³
  - 28.4 mm³
- Average porosity content 1.3%
- Median pore size
  - Equivalent diameter of 55 µm
- Average porosity in gage – 0.3%
- Average porosity in grip – 1.7%
Premier Tensile Bar
Premier Tensile Bar
Premier Tensile Bar

- 86,696 pores larger than 37 µm
- Sample weight 6.6 g
- Total volume of porosity
  - 16,600,925,090 µm³
  - 16.6 mm³
- Average porosity content 0.7%
- Median pore size
  - Equivalent diameter of 49 µm
- Average porosity in gage – 0.4%
- Average porosity in grip – 1.1%
# Thickness of the Dense Skin

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness of the Dense Skin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gage Section</td>
</tr>
<tr>
<td>NADCA tensile bar</td>
<td>1.7</td>
</tr>
<tr>
<td>Premier tensile bar</td>
<td>1.0 to 1.3</td>
</tr>
</tbody>
</table>

North American Die Casting Association
Die Casting Congress: South - March 5, 2019  San Luis Potosi, Mexico
Radial Distribution of Porosity

- Used raw data collected from CT scans
  - Quantitatively characterized radial porosity distribution
- Split grip into 10 concentric cylinders (0.5 mm wide)
- Added up volume of porosity in each cylinder
Radial Distribution of Porosity - Grip

- Porosity is 4-5% at the centerline
- Essentially zero at the surface

![Graph showing the radial distribution of porosity](image-url)
Radial Distribution of Porosity - Gage

- Porosity is 4-5% at the centerline
- Essentially zero at the surface
Porosity at Centerline

- Porosity at the centerline of the tensile bars is ~4-5%
  - For both grip & gage
- Alloy 383 contains 9.5-11.5% Si
  - Volumetric shrinkage on solidification for alloy 383 is about 4.5%
- So is most of the porosity at the centerline shrinkage porosity?

Solidification shrinkage as a function of silicon content for Al-Si alloys
## Thickness of the Dense Skin

- Measured from porosity profiles (<0.1% porosity)

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness of the Dense Skin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gage Section</td>
</tr>
<tr>
<td>NADCA tensile bar</td>
<td>0.6</td>
</tr>
<tr>
<td>Premier tensile bar</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- Measured visually from scans

<table>
<thead>
<tr>
<th>Sample</th>
<th>Thickness of the Dense Skin (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gage Section</td>
</tr>
<tr>
<td>NADCA tensile bar</td>
<td>1.7</td>
</tr>
<tr>
<td>Premier tensile bar</td>
<td>1.0 to 1.3</td>
</tr>
</tbody>
</table>
Sphericity

• Can sphericity ($\Psi$) be used to distinguish between shrinkage porosity and gas porosity?

  • Gas pores should be more spherical
    • Sphericity closer to 1
  • Shrinkage pores should be irregular in shape
    • Lower level of sphericity

$$\Psi = \frac{\pi^{1/3} (6V_p)^{2/3}}{A_p}$$

  • Calculated sphericity as a function of radius

$V_p = $ volume of pore
$A_p = $ surface area of pore
Sphericity & Porosity

Legend: Solid line = % porosity; dotted line = sphericity

NADCA grip

Premier grip

NADCA gage

Premier gage

North American Die Casting Association
Die Casting Congress: South - March 5, 2019  San Luis Potosi, Mexico
Sphericity

- Center of tensile bars
  - Should contain both shrinkage and gas pores
  - Average sphericity ~ 0.5
- Surface of tensile bars
  - Should be mostly gas porosity
  - Average sphericity ~ 0.6
- Further work is required to determine if the sphericity parameter can be used to distinguish between gas and shrinkage porosity
Summary & Conclusions

• Objective was to use x-ray micro-tomography (CT scanning)
  • To examine the size and distribution of porosity in high pressure die castings

• Samples characterized were sections approximately 2-inches long
  • Cut from cast-to-size tensile bars
  • Produced in two different dies
  • Micro-CT process could identifying pores $\geq 36 \, \mu m$
Summary & Conclusions

• Section cut from tensile bar produced in NADCA die
  • Contained more than 64,000 pores larger than 36 µm
  • Average porosity content of 1.3%

• Section cut from tensile bar produced in Premier die
  • Contained more than 86,000 pores larger than 37 µm
  • Average porosity content of 0.7%

• Porosity was not uniformly distributed
  • More pores in the center (~ 5%)
  • Fewer pores at the surface (close to 0%)
  • Dense skin was thicker than previously reported
Summary & Conclusions

• An initial attempt was made to use sphericity to distinguish between gas porosity and shrinkage porosity
Future Work

• Utilize micro-CT scanning to quantitatively determine the porosity distribution in additional die castings

• Use micro-CT scanning to determine the impact of die casting parameters on the porosity distribution and the thickness of the dense skin
  • Injection parameters
  • Intensification pressure
  • Component shape
  • Lubricants

• Can sphericity (or some other parameter) be used to distinguish between gas porosity and shrinkage porosity?

• Can actual porosity content be imported into structural model to predict mechanical performance?