CHAPTER 3

RESULTS AND DISCUSSION

3.1 INTRODUCTION

In this chapter the characterisation results obtained from visual examination, radiography, density measurement, porosity determination, visual examination of cut-section analysis, compression testing and hardness measurement of developed porous gunmetal castings are presented and discussed. Further the characterisation results obtained from visual examination, radiography test, density measurement and porosity determination of both porous stainless steel and porous aluminium castings are also presented.

Four gunmetal castings, five stainless steel castings and five aluminium castings were developed in this research work. Figure 3.1 shows the images of fourteen porous castings developed.

![Developed porous castings](image-url)
3.1.1 Porous Gunmetal Castings

In this research work four gunmetal castings were developed and tested for porosity formation. Figure 3.2 shows the four gunmetal castings developed.

![Porous gunmetal castings](image)

**Figure 3.2 Porous gunmetal castings**

3.1.1.1 Visual examination

Visual examination is considered as the most effective non-destructive test to confirm the formation of pores throughout the casting samples. The porous casting samples after removal from the mould cavity are cleaned by shot blasting. Air jet cleaning was also carried out to remove the sand balls clearly from the casting surface to confirm the formation of pores.

Porous castings after removal of sand balls were visually inspected. Four casting samples were produced by varying the sand ball sizes from 15mm to 30mm. Experiment 1 was conducted with 15mm sand ball sizes, experiment 2 with 20mm sand ball sizes, experiment 3 with 25mm sand ball sizes.
sizes and experiment 4 with 30mm sand ball sizes. The porous castings are shown in Figure 3.3 to Figure 3.6.

Figure 3.3 Visual examination of experiment 1 (gunmetal)

Figure 3.4 Visual examination of experiment 2 (gunmetal)
Figure 3.5 Visual examination of experiment 3 (gunmetal)

Figure 3.6 Visual examination of experiment 4 (gunmetal)
The visual examination results confirms the formation of porosity all over the surfaces of developed gunmetal castings. Further from Figure 3.3 to Figure 3.6 the shape of pores formed directly depend on the shape of sand balls used for the experiments. Also from the figures it is well confirmed that the pores are evenly distributed on the entire casting surfaces.

### 3.1.1.2 Radiography test

Ali Bateni et al (2008) reported that the final images from radiography test confirm that the darker regions on the film represented the more penetrable part of the object and the lighter regions are more opaque in radiation.

The four experimental samples were taken for radiographic test to evaluate the formation of pores all through the interior parts of the metal. Experiment 1 represents the radiography result of cut section sample having dimension of the size 75mmx75mmx65mm. Experiment 2 to experiment 4 represents radiography result of size 150mmx150mmx65mm. The dark region on the film represents the more penetrable part of the object than the light regions which were opaque. Figure 3.7 to Figure 3.10 shows the radiographic image results of experiments 1 to 4 for selected sand ball sizes (15mm to 30mm).
Figure 3.7 Radiographic image of experiment 1 (gunmetal)

Figure 3.8 Radiographic image of experiment 2 (gunmetal)
Figure 3.9 Radiographic image of experiment 3 (gunmetal)

Figure 3.10 Radiographic image of experiment 4 (gunmetal)
The result images of radiographic test clearly reveal the fact that the pores are mostly interconnected. The results of radiography confirm the formation of porosity in the gunmetal. It is clearly evident that the radiation has passed through the section containing void than through the surrounding metal and no mass segregation of metal. Images seen in Figure 3.7 of experiment 1, confirms that the maximum radiation has passed through the void than the surrounding metal. Here maximum radiation noticed because, this sample has maximum percentage of porosity of 62.15% with a minimum density of $3.3 \times 10^{-6}$ kg mm$^{-3}$ and thus there is no mass segregation of metal.

The images shown in Figure 3.10 confirm that the amount of radiation level is less when compared to other samples because it has minimum porosity of 52.98%. Hence the radiation cannot pass through the solid regions. A dark spot reflects the position of the void.

3.1.1.3 Density measurement

Mechanical property of metal foams largely depends on density. Density is a physical characteristic, and is a measure of weight per unit volume of a metal of substance. The weight of the sample is found using a digital balance and volume is measurable and that can be measured. By dividing the weight of the samples to its volume gives its density.

The density measurement and calculation of non-porous sample and porous castings are tabulated in Table 3.1. Density calculations are made using the Equation 2.1.
### Table 3.1 Weight and Density of gunmetal samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Casting size, mm</th>
<th>Weight, kg</th>
<th>Density x10^{-6} kgmm^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>150x150x65</td>
<td>12.75</td>
<td>8.72</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>15</td>
<td>150x150x65</td>
<td>4.85</td>
<td>3.3</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>20</td>
<td>150x150x65</td>
<td>5.67</td>
<td>3.9</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>25</td>
<td>150x150x65</td>
<td>5.2</td>
<td>3.6</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>30</td>
<td>150x150x65</td>
<td>6.0</td>
<td>4.1</td>
</tr>
</tbody>
</table>

Measuring the density of porous materials is one of the most important factors to be considered (Ali Bateni et al 2008). The density of non-porous castings was taken as $8.72 \times 10^{-6}$ kgmm$^{-3}$ with a weight of 12.75 kg.

The experiment 1 gave minimum density of $3.3 \times 10^{-6}$ kgmm$^{-3}$ with maximum percent porosity of 62.15% with a minimum weight of 4.85 kg when the sand ball size at 15mm.

The experiment 4 gave maximum density of $4.1 \times 10^{-6}$ kgmm$^{-3}$, which gave minimum percentage of porosity of 52.98% with maximum weight at 6 kg. They are in acceptance with research findings of John Banhart (2000), that the porous castings are characterised in terms of their density, since density reflects the mechanical properties of porous structures.

#### 3.1.1.4 Porosity measurement

The measure of porosity in gunmetal is an important factor for confirming the nature of sample. Percent porosity is a rough measure of the open volume equal to 100% minus the part density. Percentage porosity is
calculated by using the Equation 2.2. Bulk density is considered as the density of non-porous sample. Achieved density is calculated using the Equation 2.1. Percentage porosity for non-porous and porous samples is tabulated in the Table 3.2.

### Table 3.2 Percent porosity of gunmetal samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Weight, kg</th>
<th>Density $\times 10^{-6}$ kg/mm$^3$</th>
<th>% porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>12.75</td>
<td>8.72</td>
<td>Nil</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>15</td>
<td>4.85</td>
<td>3.3</td>
<td>62.15</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>20</td>
<td>5.67</td>
<td>3.9</td>
<td>55.27</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>25</td>
<td>5.2</td>
<td>3.6</td>
<td>58.71</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>30</td>
<td>6.0</td>
<td>4.1</td>
<td>52.98</td>
</tr>
</tbody>
</table>

In experiment 1 from this research work on gunmetal, maximum percent porosity of 62.15% was achieved at a minimum density of $3.30 \times 10^{-6}$ kg/mm$^3$ weight at 4.85 kg when the sand ball size at 15mm. Franstisek Simansik (2001) reported that the volume of cores used is maximum (accommodation of maximum amount of performs in the die). Less amount of liquid metal required in filling the voids and interconnectivity is more, thus maximum percentage of porosity achieved.

In experiment 2, when the sand ball size at 20mm, the percent porosity of 55.27% was achieved with weight at 5.67 kg at a density of $3.9 \times 10^{-6}$ kg/mm$^3$. 
In experiment 3, when the sand ball size at 25mm, the percent porosity of 58.71% was achieved with weight at 5.2 kg at a density of 3.6x10^{-6} kg mm^{-3}.

In experiment 4, minimum porosity of 52.98% was achieved at maximum density of 4.10x10^{-6} kg mm^{-3} with weight at 6.0 kg when the ball size at 30mm, due to less amount of prefoms and more metal accommodation in to the die.

Thus the result of porosity measurement reflects that the percentage of porosity level increases with decrease in density and the percentage of porosity decreases with increase in density.

Hence the result analysis confirms the formation of porosity in gunmetal castings. There exists a direct relation between density and porosity and it is given in Figure 3.11.

Figure 3.11 Density Vs percentage porosity (gunmetal)
3.1.1.5 Visual examination of cut-section

Porous gunmetal casting samples obtained from the experiment 1 to experiment 4 were cut into four equal halves with dimension 75mmx75mmx65mm size to further examine, visually the distribution of pores and to confirm the foam formation and interconnectivity of pores, shot blasting and water jet was used to clean the pores to remove the sand balls. The shape and size of the pores depends directly on size and geometry of the cores used. Figure 3.12 to Figure 3.15 are the cut-section images of the porous samples produced using different core sizes from 15mm to 30mm.

Figure 3.12 Cut-section image of experiment 1 (gunmetal)
Figure 3.13 Cut-section image of experiment 2 (gunmetal)

Figure 3.14 Cut-section image of experiment 3 (gunmetal)
Figure 3.15 Cut-section image of experiment 4 (gunmetal)

The results of visual examination confirm the porosity formation in gunmetal castings. From visual examination of cut-section, it is very clear of pore formation and confirms that the pores are mostly interconnected within the castings. From Figure 3.12 the pores are interconnected and the percent porosity was maximum with 62.15%.

This is in agreement with research findings of Banhart and Baumeister (1998) that the shape and size of the pores depend directly on cores. The molten metal fills the voids in between the cores filled in the die and nucleation starts at the surface of the cores.

3.1.1.6 Compression test

Mechanical stability of metallic foams is determined by compression testing. Compression testing plays an important role in
characterisation of metallic foams. The cut-sections were taken to universal testing machine for determining the behaviour of materials under crushing loads. Figure 3.16 shows the cut sample undergoing compression in universal testing machine.

![Cut specimen undergoing compression](image)

**Figure 3.16 Cut specimen undergoing compression**

All the four experimental samples were tested for their mechanical stability under crushing loads. Figure 3.17 to Figure 3.20 shows four experimental cut samples after compression test. Results are tabulated in Table 3.3.
Figure 3.17 Experimental 1 sample after compression

Figure 3.18 Experimental 2 sample after compression
The breakable load of non-porous casting extended upto 450 KN, because it is a full solid. The porous samples gave breakable load values from 169 KN to 239 KN. The results are tabulated in Table 3.3.
Table 3.3 Compression load on gunmetal samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size mm</th>
<th>Size of sample, mm</th>
<th>Density $x10^{-6}$ kgmm$^{-3}$</th>
<th>Breakable load (KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>75x75x65</td>
<td>8.72</td>
<td>450</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>15</td>
<td>75x75x65</td>
<td>3.3</td>
<td>169</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>20</td>
<td>75x75x65</td>
<td>3.9</td>
<td>229</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>25</td>
<td>75x75x65</td>
<td>3.6</td>
<td>209</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>30</td>
<td>75x75x65</td>
<td>4.1</td>
<td>239</td>
</tr>
</tbody>
</table>

The variation in compression load values from 169 KN to 239 KN were based on the porous nature of the samples and their load deformation limits. When the density decreases the compressive strength of the casting also decreases. There exists a direct relationship between density and compressive load bearing capacity of the metal and it is given in Figure 3.21.

![Density Vs Compressive strength](image)

Figure 3.21 Density Vs compressive strength (gunmetal)
The compressive test confirms that the maximum deformation was seen in porous casting when the density was at minimum and the porosity at maximum, minimum deformation when the density was at maximum and porosity at minimum. This is in agreement with findings of researcher Ashby et al (2000) in compressive loading, foams densify when compressed. The plastic constraint associated with indentation of dense solids is lost, and the distribution of displacement beneath the indent changes as the sample deformed completely.

3.1.1.7 Hardness test

The hardness testing result reveal the maximum deformation loads capacity of porous castings. All the four gunmetal samples were tested with Vickers hardness tester at 10 kg load and the results are tabulated in Table 3.4.

**Table 3.4 Vickers Hardness of gunmetal samples**

<table>
<thead>
<tr>
<th>Item</th>
<th>VHN at 10 kg load</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experiment 1</td>
<td>96.9</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>83</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>81.07</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>91.08</td>
</tr>
</tbody>
</table>

The experiment 1 gave the maximum hardness of 96.9 VHN and the experiment 3 gave minimum of 81.07 VHN. Hardness was measured on the solid area of the porous castings and it does not show any relation to porosity.
3.1.2 Porous Stainless Steel Castings

In this research work five stainless steel castings were developed and are shown in Figure 3.22. All the five samples were tested for confirmation of pore formation.

![Figure 3.22 Developed stainless steel castings](image)

3.1.2.1 Visual examination

To confirm the formation of pores throughout the casting samples, visual examination was carried out on all five castings. After heat treatment and acid pickling, water jet cleaning was also carried out to remove the sand balls clearly from the casting.

Five porous stainless steel samples were produced by varying the sand ball sizes from 7.5mm to 15mm. Experiment 1 was conducted with sand ball size of 7.5mm, experiment 2 was conducted with sand ball size of 10mm and experiment 3 to experiment 5 were conducted with sand ball size of 15mm. Acid pickling was not carried out for experiment 1. The result images
are shown from Figure 3.23 to Figure 3.27. Top surface view of all samples is shown from Figure 3.28 to Figure 3.32.

Figure 3.23 Visual examination of experiment 1 (stainless steel)

Figure 3.24 Visual examination of experiment 2 (stainless steel)
Figure 3.25 Visual examination of experiment 3 (stainless steel)

Figure 3.26 Visual examination of experiment 4 (stainless steel)
Figure 3.27 Visual examination of experiment 5 (stainless steel)

Figure 3.28 Top surface view of experiment 1 (stainless steel)
Figure 3.29 Top surface view of experiment 2 (stainless steel)

Figure 3.30 Top surface view of experiment 3 (stainless steel)
Figure 3.31 Top surface view of experiment 4 (stainless steel)

Figure 3.32 Top surface view of experiment 5 (stainless steel)
From images shown from Figure 3.23 to Figure 3.27, the result and discussion of visual examination confirms the formation of pores on all the surface of the casting. It is clear from the top surface view shown from Figure 3.28 to Figure 3.32 that the pores formed mostly have interconnectivity. Also the size and shape of the pores directly depend on the shape and size of the sand balls used for the experiments.

It is noticed from the visual examination of experiment 1 that corrosion has taken place in the metal, where as the results from experiment 2 to experiment 5 remained corrosion resistant. In experiment 1, pickling was not conducted to the sample. The passive state of the metal was broken down and the surface became active to corrosion. This accepts the findings of Roger Crookes (2007) that acid pickling improves the passivation by remaining the surface where the chromium level has been reduced. Hence corrosion resistance of the metal improved for the samples in experiment 2 to experiment 5 when subjected to acid pickling.

3.1.2.2 Radiography test

All the five porous stainless steel samples developed were subjected to radiographic test for analyzing the pores formed in the metal. The radiography test results are shown in Figure 3.33 to Figure 3.37.
Figure 3.33 Radiographic image of experiment 1 (stainless steel)

Figure 3.34 Radiographic image of experiment 2 (stainless steel)
Figure 3.35 Radiographic image of experiment 3 (stainless steel)

Figure 3.36 Radiographic image of experiment 4 (stainless steel)
The discussion of the results of radiography confirms the formation of porosity in the stainless steel samples. It is clearly evident that the radiation has passed through the section containing the void than through the surrounding metal and there is no mass segregation of the metal. The image seen from Figure 3.34 of experiment 2 confirms that the maximum radiation passed through the portion containing void than the surrounding metal. This maximum amount of radiation on the sample was noticed because the percentage of porosity was at the maximum at the density of $3.60 \times 10^{-6}$ kg/mm$^3$.

The radiography images also clearly reveal the fact that the pores are mostly interconnected. The images shown in Figure 3.36 of experiment 4 confirm the radiation level of very low when compared to other samples because the porosity was minimum at 46.42% with the density of $4.20 \times 10^{-6}$ kg/mm$^3$. Hence the radiation cannot pass through the solid regions.
Hence the results of radiography tests on porous stainless steel agrees with the findings of Ali Bateni et al (2008) that the final images of radiography test confirms that the darker region on the film represented the penetrable parts on the object and the lighter regions are more opaque.

### 3.1.2.3 Density measurement

The results obtained from the density measurement are tabulated in Table 3.5. The density of non-porous casting was taken as $7.84 \times 10^{-6}$ kgmm$^{-3}$ with weight of 29.40 kg. Hence there is no porosity formation for the non-porous sample.

#### Table 3.5 Weight and Density of stainless steel samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Casting size, mm</th>
<th>Weight, kg</th>
<th>Density $\times 10^{-6}$ kgmm$^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>250x250x60</td>
<td>29.40</td>
<td>7.84</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>7.5</td>
<td>250x250x60</td>
<td>13.80</td>
<td>3.68</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>10</td>
<td>250x250x60</td>
<td>13.50</td>
<td>3.60</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>15</td>
<td>250x250x60</td>
<td>14.86</td>
<td>3.96</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>15</td>
<td>250x250x60</td>
<td>15.75</td>
<td>4.20</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>15</td>
<td>250x250x60</td>
<td>14.50</td>
<td>3.86</td>
</tr>
</tbody>
</table>

The result of density measurement of porous sample gave changes in the density value. The experiment 2 gave the minimum density of $3.60 \times 10^{-6}$ kgmm$^{-3}$ and porosity of 54.08% at a minimum weight of 13.50 kg.

The experiment 4 gave maximum density of $4.20 \times 10^{-6}$ kgmm$^{-3}$ at a minimum porosity of 46.42% with the maximum weight at 15.75 kg. Hence
they are in agreement with the findings of John Banhart (2000) that the porous castings are characterised in terms of their density. Since the mechanical properties of porous materials largely depend on density.

3.1.2.4 Porosity measurement

The measure of porosity formation in stainless steel is an important factor for confirming the nature of the sample. In this research percentage of porosity for non-porous and porous samples are tabulated in Table 3.6

Table 3.6 Percent porosity of stainless steel samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Weight, kg</th>
<th>Density x10^{-6} kgmm^{3}</th>
<th>% porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>29.40</td>
<td>7.84</td>
<td>Nil</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>7.5</td>
<td>13.80</td>
<td>3.68</td>
<td>53.06</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>10</td>
<td>13.50</td>
<td>3.60</td>
<td>54.08</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>15</td>
<td>14.86</td>
<td>3.96</td>
<td>49.48</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>15</td>
<td>15.75</td>
<td>4.20</td>
<td>46.42</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>15</td>
<td>14.50</td>
<td>3.86</td>
<td>50.76</td>
</tr>
</tbody>
</table>

Initially weight of non-porous sample was calculated as 29.40 kg with the density of 7.84x10^{-6} kgmm^{-3} with nil percentage of porosity.

The development of porosity for experiment sample from experiment 1 to experiment 5 confirms the formation of porosity in stainless steel. Experiment 2 gave the maximum porosity of 54.08% with the weight of 13.50 kg at a density of 3.60x10^{-6} kgmm^{-3} when the sand ball size at 10mm.
The Minimum percentage porosity of 46.42% was achieved in experiment 4 at a maximum weight of 15.75 kg at a density of 4.20x10^{-6} kgmm^{-3}. Thus from the result of porosity development, it is seen that the percentage porosity level increases when the density decreases and percentage level decreases with an increase in density. They are in agreement with the research findings of Ashby et al (2000).

Hence the result confirms the formation of porosity in stainless steel castings. There exists a direct relation between porosity and density and it is given in Figure 3.38.

![Density vs Percentage porosity](image)

**Figure 3.38 Density Vs porosity (stainless steel)**

### 3.1.3 Porous Aluminium Castings

In this research work five porous aluminium castings were developed and are shown in Figure 3.39. All the five castings were tested for confirmation of pores. The castings were visually examined and radiography test was conducted. Density and porosity were measured and the results are presented for discussion.
Visual examination of all five porous castings was carried out after cleaning by shot blasting. Air jet cleaning was also carried out to remove the sand balls clearly from the castings. Visual examination is considered as the most effective test to sense and confirms the pores formed and its nature.

Five castings were produced by varying the sand ball sizes from 10mm to 25mm. Experiment 1 was conducted with 10mm sand ball sizes, experiment 2 and experiment 3 were conducted with 15mm sand ball sizes, experiment 4 was conducted with 20mm sand ball sizes and experiment 5 with sand ball size of 25mm. The result images are shown in Figure 3.40 to Figure 3.44. Figure 3.45 to Figure 3.49 shows the top view image of porous castings.
Figure 3.40 Visual examination of experiment 1 (aluminium)

Figure 3.41 Visual examination of experiment 2 (aluminium)
Figure 3.42 Visual examination of experiment 3 (aluminium)

Figure 3.43 Visual examination of experiment 4 (aluminium)
Figure 3.44 Visual examination of experiment 5 (aluminium)

Figure 3.45 Top surface view of experiment 1 (aluminium)
Figure 3.46 Top surface view of experiment 2 (aluminium)

Figure 3.47 Top surface view of experiment 3 (aluminium)
Figure 3.48 Top surface view of experiment 4 (aluminium)

Figure 3.49 Top surface view of experiment 5 (aluminium)
The result of visual examination confirms the porosity formation in aluminium castings. Figure 3.40 to Figure 3.44 confirm the formation of pores on all the surfaces of the castings.

From the top face view shown in Figure 3.45 to Figure 3.49, it is confirmed that the pores are mostly interconnected. It confirms the formation of porosity between each wall of the samples. The shape and sizes of the pores depends directly on the cores used. This is in agreement with the findings of Banhart and Baumeister (1998). It is confirmed that the formation of pores are clearly identified.

3.1.3.2 Radiography test

All the five porous aluminium samples developed were subjected to radiographic test for analysing the pores formed. The results of radiography tests are shown in Figure 3.50 to Figure 3.54.

Figure 3.50 Radiographic image of experiment 1 (aluminium)
Figure 3.51 Radiographic image of experiment 2 (aluminium)

Figure 3.52 Radiographic image of experiment 3 (aluminium)
Figure 3.53 Radiographic image of experiment 4 (aluminium)

Figure 3.54 Radiographic image of experiment 5 (aluminium)
The radiographic images clearly reveal the fact that the pores are interconnected.

The discussion of the results of radiography test confirms that there is porosity formation in all the developed aluminium castings. It was clearly seen that the radiation has passed through the section containing void than the surrounding metal and no mass segregation noticed.

The image seen in Figure 3.54 of experiment 5 confirms that the maximum radiation has passed through the section containing the void than through the surrounding metal. Here the maximum percent porosity at 57.73% with a density of 1.12x10^-6 kg mm^-3, so the maximum amount of radiation was seen. No mass segregation of metal was noticed.

Figure 3.50 of experiment 1 confirms that the level of radiation was less compared to the other samples because the sample with a minimum percent porosity of 40.37% at a maximum density of 1.58x10^-6 kg mm^-3. Hence the radiation cannot pass through the solid regions.

The results of radiography test are in agreement with the findings of Ali Bateni et al (2008), that the final images from the radiography test confirms that the lighter regions are more opaque in radiation and the darker regions are more penetrable parts on the object.

### 3.1.3.3 Density measurement

The density of non-porous and the density of developed porous castings are given in Table 3.7. The density of non-porous LM6 aluminium was taken as 2.65x10^-6 kg mm^-3 with a weight of 9.93 kg. Experiment 1 to experiment 5 was conducted with changing the sand ball sizes from 10mm to 25mm.
Table 3.7 Weight and Density of aluminium samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Casting size, mm</th>
<th>Weight, kg</th>
<th>Density x10^-6 kgmm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>250 x 250 x 60</td>
<td>9.93</td>
<td>2.65</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>10</td>
<td>250 x 250 x 60</td>
<td>5.95</td>
<td>1.58</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>15</td>
<td>250 x 250 x 60</td>
<td>5.55</td>
<td>1.48</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>15</td>
<td>250 x 250 x 60</td>
<td>5.85</td>
<td>1.56</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>20</td>
<td>250 x 250 x 60</td>
<td>5.90</td>
<td>1.57</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>25</td>
<td>250 x 250 x 60</td>
<td>4.23</td>
<td>1.12</td>
</tr>
</tbody>
</table>

The result on density measurement of porous samples gave changes in density values. The experiment 5 gave minimum density of $1.12 \times 10^{-6}$ kg mm$^{-3}$, with percent porosity at 57.73% with a minimum weight of 4.23 kg.

The experiment 1 gave maximum density of $1.58 \times 10^{-6}$ kg mm$^{-3}$, with percent porosity at 40.37% with a maximum weight of 5.95 kg.

Thus the results of density measurement are in agreement with the research findings of John Banhart (2000), that the porous castings are characterised in terms of their density since the mechanical properties of porous structures largely depend on the density.

3.1.3.4 Porosity measurement

The measure of porosity level formation in aluminium sample is an important factor in confirming the nature of the sample. In this research work
percent porosity measurement was analysed for porous samples. Initially the percent porosity of non-porous sample at density $2.65 \times 10^{-6}\text{kgmm}^{-3}$ with weight of 9.93 kg was considered nil. The results of porosity of samples for experiment 1 to experiment 5 are tabulated in Table 3.8.

Table 3.8 Percent porosity of aluminium samples

<table>
<thead>
<tr>
<th>Item</th>
<th>Sand ball size, mm</th>
<th>Weight, kg</th>
<th>Density $\times 10^{-6}$ kgmm$^{-3}$</th>
<th>% porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-porous</td>
<td>Nil</td>
<td>9.93</td>
<td>2.65</td>
<td>Nil</td>
</tr>
<tr>
<td>Experiment 1</td>
<td>10</td>
<td>5.95</td>
<td>1.58</td>
<td>40.37</td>
</tr>
<tr>
<td>Experiment 2</td>
<td>15</td>
<td>5.55</td>
<td>1.48</td>
<td>44.15</td>
</tr>
<tr>
<td>Experiment 3</td>
<td>15</td>
<td>5.85</td>
<td>1.56</td>
<td>41.13</td>
</tr>
<tr>
<td>Experiment 4</td>
<td>20</td>
<td>5.90</td>
<td>1.57</td>
<td>40.75</td>
</tr>
<tr>
<td>Experiment 5</td>
<td>25</td>
<td>4.23</td>
<td>1.12</td>
<td>57.73</td>
</tr>
</tbody>
</table>

In experiment 1, when the sand ball sizes at 10mm, percent porosity was very low at 40.37% at weight 5.95 kg and the density maximum at $1.58 \times 10^{-6}\text{kgmm}^{-3}$.

In experiment 2, when the sand ball size was at 15mm, the percent porosity of 44.15% was achieved at weight 5.55 kg and the density at $1.48 \times 10^{-6}\text{kgmm}^{-3}$.

In experiment 3, when the sand ball size was at 15mm, the percent porosity of 41.13% was achieved at weight 5.85 kg and the density at $1.56 \times 10^{-6}\text{kgmm}^{-3}$.
In experiment 4, when the sand ball size was at 20mm, the percent porosity of 40.75% was achieved at weight 5.90 kg and the density at 1.57x10^{-6} kg mm^{-3}.

In experiment 5, when the sand ball size at 25mm, percent porosity was maximum at 57.73%, at weight 4.23 kg and the density minimum at 1.12x10^{-6} kg mm^{-3}.

The porous sample from this research work gave maximum percent porosity of 57.73%. This is in agreement with the research findings of Frantisek Simancik (2001), that the maximum percentage porosity can be achieved when the volume of cores used is maximum (maximum amount of performs that can be accommodated in the die) and less amount of liquid metal that is required to fill the voids.

Percent porosity is a rough measure of the open volume equal to 100% minus the part density. The total open volumes of interconnected and isolated porosity are normally included in this value. According to Banhart and Baumeister (1998) porosity is a measure of the void space in the material and it is a fraction of the volume of the voids over the total volume. Hence the results from the percent porosity measurement confirm the porosity formation in aluminium.

From the results of porosity measurement it is seen that the porosity increases when the density decreases and the porosity decreases when the density increases. They are in agreement with the research findings of John Banhart (2000), that the porous castings are characterised in terms of the density since the mechanical properties of porous castings mostly depend on density. There exists a direct relation between porosity and density and is given in Figure 3.55.
3.2 CONCLUSIONS

Conclusions on developed porous gunmetal, aluminium and stainless steel castings are presented.

3.2.1 Conclusions on Gunmetal Castings

1. Porous castings of desired pore size and shape can be produced in gunmetal.

2. Visual examination of casting reveals that the pores are evenly distributed all over the casting surfaces.

3. Radiography test confirms that no mass segregation of the metal at any place in the casting and the pores are interconnected.
4. The minimum density which gave maximum percentage of porosity was $3.3 \times 10^{-6}$ kg/mm$^3$ with a weight of 4.85 kg and at a percentage porosity of 62.15%. The nonporous casting shows a density of $8.72 \times 10^{-6}$ kg/mm$^3$ and the weight is 12.75 kg.

5. There exists a definite relation between casting weight and porosity.

6. There exists a direct relation between density and porosity.

7. Percentage porosity level upto 62.15% can be produced in gunmetal.

8. The visual examination of cut-section of castings reveal the interconnectivity of the pores and the pore sizes are almost equal to the shape and size of the cores used. So the measuring of pore sizes is not required for the castings in this technique. Also this reveals the fact that the pore distribution and interconnections of the open cells.

9. Compression test confirms that due to porosity, a minimum load of 169 KN was utilized to compress the porous sample where as maximum load for non-porous model was above 450 KN.

10. Hardness test failed to show any relation to porosity, due to the fact that the hardness was measured on the solid area of the porous castings.
3.2.2 Conclusions on Stainless Steel Castings

1. Porous castings of desired pore size and shape can be produced in stainless steel.

2. Visual examination confirms the formation confirms pores on all surfaces of the castings. Pores formed on the castings are almost equal to the shape and size of the cores used. Therefore the measuring of pore sizes is not needed for the castings produced by this technique.

3. Visual examination confirms the necessity of acid pickling of stainless steel to bring the surface to a passive state to improve corrosion resistance. Without pickling, surfaces may become active to corrosion.

4. Radiography test confirms that no mass segregation of the metal at any place in the casting and the pores are mostly interconnected.

5. The minimum density which gave maximum percentage porosity was $3.60 \times 10^{-6}$ kgmm$^{-3}$ with a weight of 13.75 kg and at a percentage porosity of 54.08%. The nonporous casting shows a density of $7.84 \times 10^{-6}$ kgmm$^{-3}$ and the weight is 29.40 kg.

6. Percentage porosity level upto 54.08% can be produced in stainless steel castings.

7. There exists a definite relation between weight and porosity and also a direct relation between density and porosity.

3.2.3 Conclusions on Aluminium Castings

1. Porous castings of desired pore size and shape can be produced in aluminium.
2. Visual examination confirms the formation of pores on all the surfaces of the castings. Pores formed on the castings are almost equal to the shape and size of the cores used. Therefore the measuring of pore sizes is not required for the castings produced by this technique.

3. Radiography test confirms that no mass segregation of metal at any place of the casting and the pores are mostly interconnected.

4. The minimum density which gave maximum percentage porosity was $1.12 \times 10^{-6}$ kg/mm$^3$ with a weight of 4.23 kg and at a percentage porosity of 57.73%. The nonporous casting shows a density of $2.65 \times 10^{-6}$ kg/mm$^3$ and the weight is 9.93 kg.

5. Percentage porosity upto 57.73% can be produced in stainless steel castings.

6. There exists a definite relation between weight and porosity and also a direct relation between density and porosity.

3.3 OVERALL CONCLUSIONS BASED ON THIS RESEARCH

1. Porous castings can be produced in all types of metallic materials like aluminium, gunmetal and stainless steel.

2. Casting around granules technique can be adopted for all type of metals to develop porous castings.

3. Size and shape of the pores are almost equal to the size and shape of the cores used for developing the porous castings.
4. Maximum porosity can be achieved when the volume of the cores used was kept maximum (less volume of metal was required to fill the cavity).

5. Maximum porosity was achieved when the density was minimum.

6. Radiography test confirms the interconnectivity of pores and also confirms no mass segregation of the metal.

7. Visual examination of cut-section of porous gunmetal castings reveal the interconnections of the open cells.

8. Compression test on porous gunmetal confirms the fact that a minimum load of 169 KN was utilized to compress when compared to 450 KN that was utilized to compress non-porous metal.

9. Hardness test on gunmetal failed to show any relation to porosity.

3.4 SUGGESTIONS FOR FUTURE RESEARCH

1. DOE can be attempted by increasing the sample sizes using casting around granules method.

2. Analysis also can be carried out in different pouring temperatures using same metals.

3. Experimental analysis can be carried out by changing the sand ball sizes and also changing the sand ball materials like ceramic balls.

4. Microstructure analysis and SEM analysis can be attempted.

5. Analysis can be conducted by producing castings in different routes.