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# Casting of Aluminium Foam with Defined Porosity Using DoE

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## Abstract

Closed cell aluminium foam offers an interesting combination of properties such as high energy absorption, stiffness, strength and low density. These properties give it great potential as an impact absorbing material which can be used in the automotive industry, military, civil engineering and others. To achieve these properties, the structure of the foam is important. The number, shape, regularity and distribution of pores are of great importance. A major disadvantage of aluminium foam is its low viscosity and consequently poor castability.
Casting of aluminium metal foam is achieved by a thermally activated chemical reaction of the foaming agent calcium carbonate (CaCO3). Different amounts of foaming agent and reaction times have been used to achieve defined porosity. With regard to process stability and manufacturing cost, optimal parameters to achieve defined porosity were found using DoE (Design of Experiment) methodology. As a result, longer agitation times were found to produce more homogeneous foams as the calcium carbonate powder was better distributed, consequently more calcium carbonate powder needs to be added as it reacts and is consumed when in contact with the melt. Experiments were performed using gravity casting and simple shapes can be made this way. Efforts are currently being made to establish a manufacturing process that can be used to produce castings with defined geometry.

**Keywords:** Metal foam, Aluminium foam, Design of experiment, Powder foaming agent, Aluminium foam production

## 1. Introduction

Porous materials are known for their unique properties such as low density, high strength-to-weight ratio, impressive mechanical and thermal mechanical and thermal properties. These properties have inspired engineers to mimic these structures and develop engineered porous materials such as structures and develop engineered porous materials such as polymer foams and metal foams. Metal foams offer new combinations of physical, mechanical, thermal, electrical and acoustic properties, while offering high stiffness to weight ratio and low thermal conductivity. These ideal for applications requiring lightweight and rigid structures, efficient energy absorption, thermal management and acoustic absorption, thermal management and acoustic control. [1-6]

Aluminium foams are not widely used because of its high manufacturing cost, there has been efforts to lower the manufacturing cost by using cheaper foaming agents as $CaCO_3$. Although the results are promising, there has not been any success in making aluminium foam with defined porosity, part of this research is testing the benefits of Design of Experiment approach. Using this approach the process parameters will be improved to such an extent that a perfectly homogeneous structure foam is produced. [7-9]

The work focuses on the production method of direct foaming by adding a gas releasing blowing agent to the metal and the determination of the dependencies of the individual production parameters to achieve optimal foam properties.

The goal of this research is to establish stable process for casting aluminium foam using modified Alporas technology. The added value of this research is in the change of foaming agent which promises reduced cost and manufacturing time. This goal is achieved by using significantly cheaper foaming agent $CaCO_3$ instead of $TiH_2$ and as an consequence loosing one step in preparation of the melt as the melt is being thickened by the Ca released from the foaming agent.

## 2. Technology

Technology used in this research is modified Alporas, which has been modified by using calcium carbonate ($CaCO_3$) as foaming agent as well as a viscosity modificatory instead of using plain Ca as viscosity modifier and $TiH_2$ as foaming agent. This approach allowed to merge the two stages of modifying and foaming to one cojoined stage. This all is in favour of simplification of the process and therefore possible increase of reliability. [4, 11, 12]

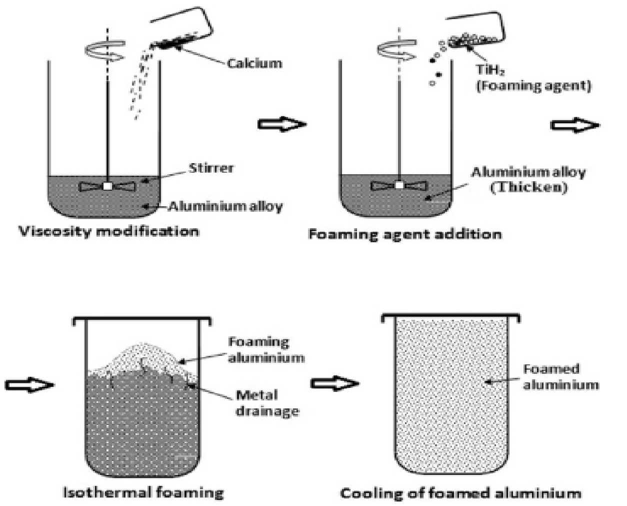


Fig. 1 Alporas technology scheme [10]

As seen in Fig. 1 Alporas technology consists of four steps as the modifier (Ca) and foaming agent ($TiH_2$) has to be added separately, by using $CaCO_3$ these two steps merge into one.

This new technology promises significant cost reduction as $TiH_2$ (800 EUR/Kg) is substituted by $CaCO_3$ (1 EUR/Kg) which has much lower cost. Results obtained using this technology are promising as well and do not deviate too much from results obtained by the original Alporas technology. [2, 3]

## 3. Work methodology

Experiment was constructed using DoE which offers a way to design the experiment effectively. Next chapter will be dedicated to designing the experiment using DoE.

Experiment was conducted using cast iron crucibles which were used to melt the aluminium alloy (AlSi5) in induction furnace, foaming agent (CaCO3) was added to the crucible before melting and was packed in aluminium foil for ease of manipulation with specimens. Each charge was weighted and corresponding amount of foaming agent was packed into aluminium foil and added into crucible before melting.

Melting was performed without protection atmosphere. As the charge was melted agitation were to begun, the stated time of reaction is the agitation time. After agitation crucible was extracted form furnace and immediately cooled with water. Rapid cooling of the specimens ensures homogenous porosity. Resulting specimens were cut to blocks for easier calculation of porosity.

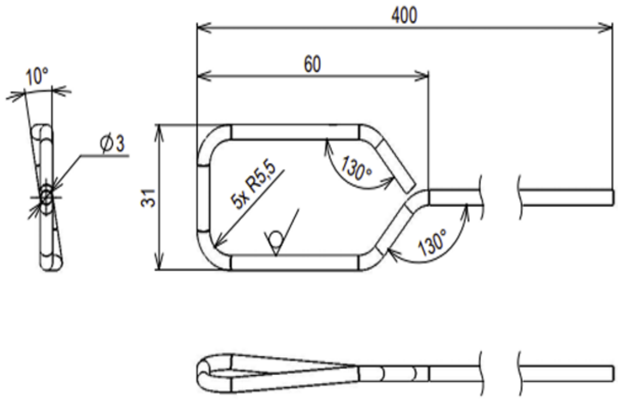


Fig. 2 Agitator made from welding rod

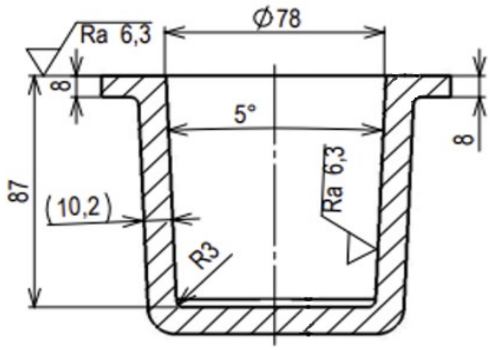


Fig. 3 Crucible geometry

Drawing of used agitator and crucible has been included in Fig. 2 and Fig. 3 as it has undeniable influence on quality of the foam.

## 4. Design of Experiment

DOE is a powerful tool that allows scientists to extract the maximum amount of data while minimising the amount of data collection. By using factorial designs, the causes and effects of multiple factors can be studied simultaneously, avoiding the need for separate studies that vary only one factor at a time. This approach allows the sensitivity of each factor and the interactions between different factors to be assessed. It is important to note that traditional studies that focus on only one factor separately do not provide insight into these interactions. This highlights the advantage of using DOE techniques to test and evaluate engineered systems.

## 4.1. Designing the Experiment

It is necessary to select the variables to be studied and to fix the remaining ones. A brief overview of the variables and how to set them is shown in Fig. 4. The factors that have one of the greatest effects on the final properties and that are easy to control and measure are the mass % CaCO3 and the mixing time. Therefore, they were chosen as the parameters to be studied by the DOE method.

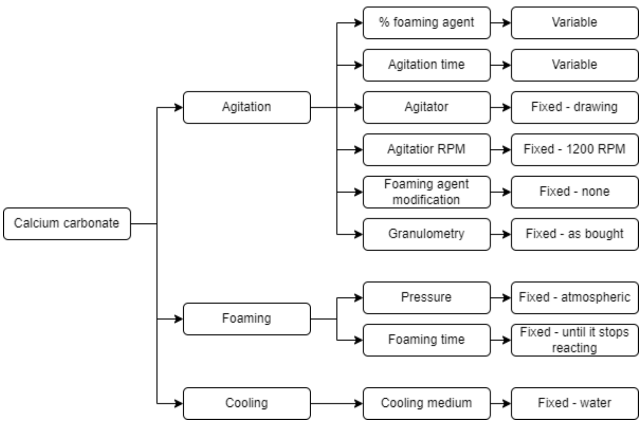

Fig. 4 Variables overview

Full factorial was chosen as the design type for the experiments. This is the deepest form of DOE that allows the observation of all interactions. The number of levels determines the number of points to be examined for regression analysis, and since a linear progression is assumed, 2 levels were chosen. 2 levels are not able to show nonlinearity of the function but were chosen to make the first attempt, the research will be more comprehensive as it will be sure that this technology is viable.

Once the experiments have been carried out and evaluated, it is necessary to find a mid-point and at this point to make and evaluate a control to check whether the observed linear dependence really fits. If the control points do not fall close to the curve, it would mean that the dependence is not linear but curved and these points are used to adjust and refine the function on the curve. [13, 14]

Table 1.
Variables setting

| Specimen no. | Weight % $CaCO_3$ [%] | Agitation time [s] |
|---|---|---|
| 1 | 2 | 30 |
| 2 | 6 | 30 |
| 3 | 2 | 70 |
| 4 | 6 | 70 |

# 5. Results

Three specimens of each variant were made to verify repeatability and to obtain standard deviation. In Fig. 5 can be seen that every batch of specimens is similar enough to conclude this process to be repeatable.

As can be seen in Fig. 6 first samples were non-homogeneous and to eliminate influence of the bigger pores samples were cut only from regions that were homogenous. At later stage of research process was optimalized and homogenity was improved.

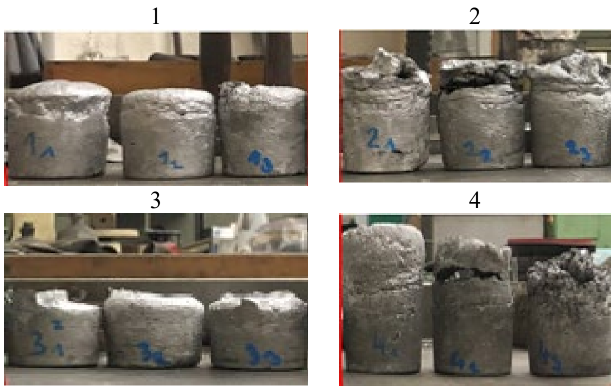

Fig. 5 Cast foams

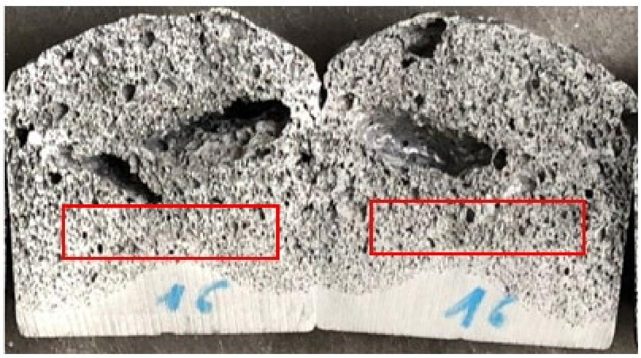
Fig. 6 Specimen cut in half, red rectangle shows the region where the block specimen was cut from

Specimens were afterwards cut into blocks and were measured and weighted. Density of porous specimen was then compared with density of specimen with 0% porosity. The density of the porous sample was then divided by the density of the 0% porosity sample to determine the percentage of porosity. Porosity of specimens can be seen in Table 2.

Table 2.
Porosity of specimens

| Specimen no. | Avg. Porosity [%] | Standard deviation [%] |
|---|---|---|
| 1 | 68 | 5 |
| 2 | 65 | 4 |
| 3 | 60 | 4 |
| 4 | 72 | 3 |

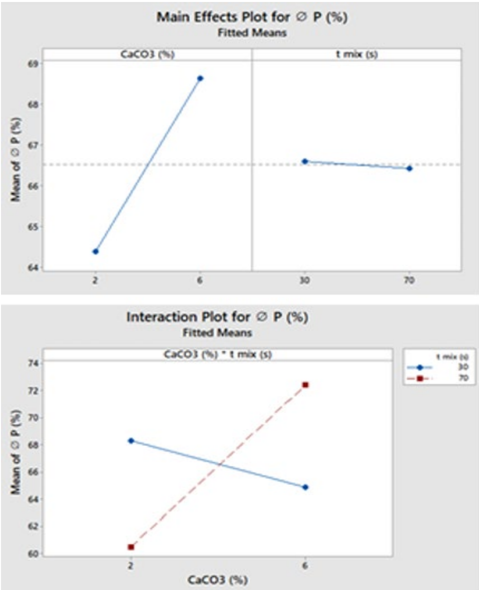


Fig. 7 Influence of isolated parameters on P[%] on top

In Fig. 7 the slope of the line describes how much given variable affects the porosity. It is apparent that when the variables are isolated (graph on top) the agitation time does not have significant influence. But in interaction with the content of the foaming agent (graph on the bottom) the significance rises. This is one of the reasons why DoE is useful and outputs better results than single variable experiment. If the experiment was conducted with just one variable it could be easily missed that the agitation time has any significant influence on porosity of the foam.

Adding to the significance of the agitation time is the fact that increasing of the agitation time results in decrease of standard deviation, which can be interpreted as improvement of repeatability of the process. Also when increasing agitation times less defects can be found in the foam. From the second graph at Fig. 7, an equation can be derived showing the relationship between the input parameters (foaming agent content and mixing time) and the resulting foam porosity. This equation can then be used to calculate the parameters required to produce foam with a defined porosity.

$$P = 81{,}67 - 3{,}73 * C - 0{,}39 * t_{mix} + 0{,}1 * C * t_{mix} \ [\%]$$

Where P stands for the porosity of specimen, C stands for the weight percentage of the foaming agent and $t_{mix}$ stands for the agitation time.

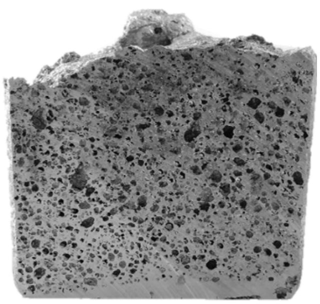

Fig. 8. Specific porosity specimen cut in half

## 5.1. Specific porosity specimens

As can be seen in Fig. 8 later samples show improved homogeneity. The improvement is mainly due to the fine-tuning of the production process. The main aspects that have contributed to the improvement of the process are: the stirrer speed, the melt temperature and the way the stirrer is removed from the melt.

Cut specimens with defined porosity with parameters defined by the stated equation can be seen in Fig. 9 and the parameters and porosity in Table 3.

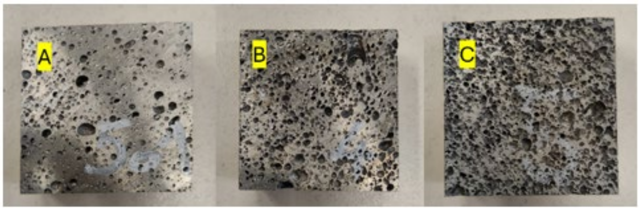


Fig. 9. Specimens made with specific porosity

Table 3.
Specific porosity specimens parameters

| Specimen | $CaCO_3$ [%] | Agit. time [s] | Porosity [%] | Targeted P [%] |
|---|---|---|---|---|
| A | 1,9 | 120 | 55 | 50 |
| B | 1,7 | 180 | 64,7 | 65 |
| C | 1,7 | 180 | 61,7 | 65 |

SEM pictures of one of the defined porosity specimens were taken and can be observed in Fig. 10. In the picture on the top, on the left side there can be seen an elongated pore, which gained its size through coalescence of original pores. This indicates that the cooling time may have been too long and the pores began to fuse. Coalescence of pores is an undesired phenomenon as it is one of the most important properties of the foam to have even and homogenous pores. Homogenous pores are essential for having most isotropic mechanical properties.

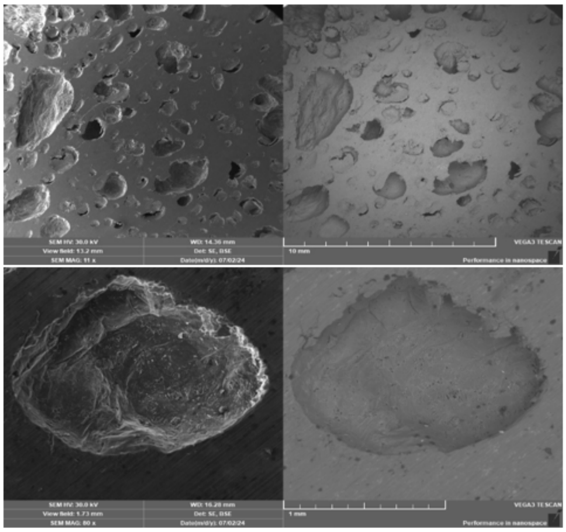

Fig. 10. SEM pictures of aluminum foam

To check the success of the modification of the melt with Ca, EDS analysis was used and attached pictures with corresponding content tables were made, Fig. 11 composition of the final aluminium foam can be read from the Table 4.

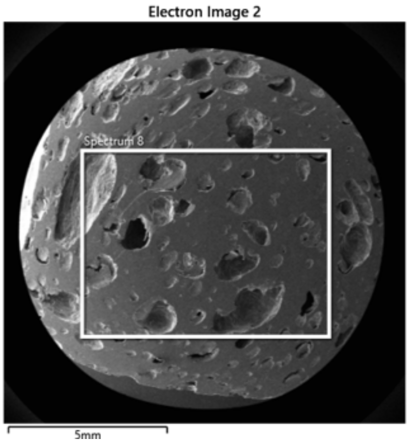


Fig. 11. SEM picture of Spectrum 8

Table 4.
Composition of Spectrum 8

| Spectrum 8 | Al | Si | O | Cu | Ca | Zn | Mg |
|---|---|---|---|---|---|---|---|
| Wt% | 75,9 | 10,7 | 10,0 | 2,1 | 0,5 | 0,5 | 0,3 |
| σ | 0,4 | 0,2 | 0,3 | 0,1 | 0,0 | 0,1 | 0,1 |

On the Fig. 12 an intermetallic phase can be seen, based on the composition it can be estimated that the phase consists of oxides and carbides formed during the decomposition of calcium carbonate, calcium carbonate decomposing into calcium and carbon dioxide can also react with the melt to form oxides and carbides of aluminium and other accompanying elements such as iron, silicon, magnesium, etc. Particularly undesirable could be the formation of silicon carbide, of which hardness could impair the machinability of the foam.


Fig. 12. SEM picture of intermetallic phase

Table 5.
Composition of Spectrum 17

| Spectrum 17 | C | O | Al | Ca | Si | Mg | Mo | Fe | Others |
|---|---|---|---|---|---|---|---|---|---|
| Wt% | 59,2 | 29,5 | 6,6 | 1,3 | 1,0 | 0,6 | 0,5 | 0,1 | 1,4 |
| σ | 0,5 | 0,4 | 0,1 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 | 0,0 |

On Fig. 13 Spectrum 12, 13, 14 and 15 were analysed. Spectrum 12 and 13 shows over 76% concentration of iron, this high content of iron can be explained as the agitator made from steel is being slowly dissolved in the melt. The temperature in the melt usually does not exceed 700°C but as induction furnace is used agitator itself is being heated and degrades. In future, agitator made from high temperature material would be necessary, to prevent contamination of the melt.

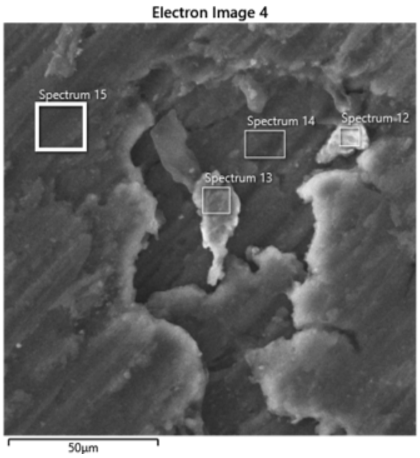


Fig. 13 SEM picture of iron inclusions

Table 6.
Composition of spectrum 12

| Spectrum 12 | Fe | Al | O | Si | Cr | Cu | Ca | Na | Mn |
|---|---|---|---|---|---|---|---|---|---|
| Wt% | 76,1 | 15,9 | 3,5 | 2,2 | 0,6 | 0,6 | 0,4 | 0,4 | 0,3 |
| σ | 0,3 | 0,2 | 0,2 | 0,1 | 0,0 | 0,1 | 0,0 | 0,1 | 0,1 |

Table 7.
Composition of spectrum 13

| Spectrum 13 | Fe | Al | O | Si | Na | Cu | Cr | Ca |
|---|---|---|---|---|---|---|---|---|
| Wt% | 76,2 | 14,7 | 3,7 | 3,5 | 0,9 | 0,4 | 0,3 | 0,2 |
| σ | 0,3 | 0,2 | 0,2 | 0,1 | 0,2 | 0,1 | 0,0 | 0,0 |

Table 8.
Composition of spectrum 14

| Spectrum 14 | Al | O | Si | Cu | Fe | Zn | Ca | Mn | Mg |
|---|---|---|---|---|---|---|---|---|---|
| Wt% | 77,0 | 9,6 | 8,8 | 2,4 | 0,6 | 0,6 | 0,3 | 0,3 | 0,3 |
| σ | 0,3 | 0,3 | 0,2 | 0,1 | 0,1 | 0,1 | 0,0 | 0,1 | 0,0 |

Table 9.
Composition of spectrum 15

| Spectrum 15 | Al | Si | O | Cu | Fe | Zn | Ca | Mn | Mg |
|---|---|---|---|---|---|---|---|---|---|
| Wt% | 80,5 | 8,3 | 7,3 | 1,8 | 0,6 | 0,5 | 0,3 | 0,3 | 0,3 |
| σ | 0,4 | 0,2 | 0,3 | 0,1 | 0,1 | 0,1 | 0,0 | 0,1 | 0,1 |

# 6. Conclusions

As it can be seen in results the manufacturing of foam with defined porosity can be achieved. DoE approach was helpful and resulted in much lower number of experiments needed to understand the issues of making aluminium foam. As only 2 factorial DoE has been chosen for this research, there is also possibility of nonlinear behaviour, so next step in this research has to be making more comprehensive observation. there is also some space to further improve this process, like adaptation of the process for industrial use as in this state it is uneconomical, slow and unprecise. A lot of specimens were discarded as unusable because of big defects. This behaviour is caused by the manual work as agitation, cooling and preparing of the charges. Some kind of agitation device as part of gating system or as a mixer incorporated in pouring ladle is suggested.

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