Micro-CT Measurements of Die-Cast Car Parts with Aluminum Foam Core

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Aluminum foams have low density, high energy absorption, and specific stiffness. Further strengthening of aluminum foam-based structures can be achieved by using a massive metallically bonded outer aluminum shell. Thanks to Aluinvent aluminum foaming technology and the developed casting processes, we can produce such parts with different shape, size, and controlled mechanical properties. Thus, aluminum foams and complex cast around structures with aluminum foam core are excellent candidates of cast three-dimensional (3D) shape car parts. Using micro-computed tomography (μ-CT) investigation in this study, we demonstrate that the developed aluminum foam cored high-pressure die cast around prototypes are having well controlled metallic bond and, during the casting process, the liquid aluminum penetrates in a controlled manner into the outer bubble layer of the solid aluminum foam.

Keywords: 3D radioscopy, micro-CT, HPDC, aluminum foam

1. Introduction

Metal foam is a cellular structure consisting of a solid metal – frequently aluminum – containing a large (50–99%) volume fraction of gas-filled pores. The pores can be sealed (closed-cell foam), or they can form an interconnected network (open-cell foam). Thanks to their porous structure, metal foams have low density, high energy absorption, high specific stiffness, excellent sound absorbing, and good vibration damping capability. Among metal foams, the closed cell aluminum foams are the most studied ones and have the highest market potential.

Up to now, closed cell aluminum foams were manufactured:
1. forming hydrogen bubbles with TiH₂ addition by
   a. Alporas [1] or
   b. Alulight processes [2] or
2. injecting the bubbles by
   a. Alcan [3],
   b. Norsk Hydro [4],
   c. Metcomb [5] or
   d. Aluinvent [6] technologies

The disadvantage of the TiH₂ addition technologies is that the remaining TiH₂ can evolve new pores during the casting process and the aluminum foam collapses during remelting. The gas injection technologies provide stable foams which do not rupture during remelting. Besides the existing products, only Aluinvent technology can provide homogeneous, machinable, and small cell sized (3–0.5 mm diameter) aluminum foams. Aluinvent new metal foaming technology resulted in a new type of metal foam called ALUHAB® which is produced with controlled cell size, wide range alloy composition, and stable mechanical properties. It is a new material which combines the weight of polymers and the strength of metals. By controlling the cell size and the alloy composition of ALUHAB, a broad density and mechanical strength combination can be achieved. This new metal foaming process is cost-efficient, resulting to stable and castable foam in different shapes, and can be also used as a core material to fabricate composite structures for the transport industry. Thus, aluminum foams can open the door to produce recyclable, improved strength metallic parts for light-weight automotive applications.

2. Production of die-cast parts

Production of aluminum foams. ALUHAB aluminum foams are produced by melting the aluminum composite, injecting the gas to the melt, and vertically pulling out the foam with a suitable bubble size, density, alloy composition, and strength. The aluminum foams produced by this method have wide density range (0.05–1.5 g/cm³), high specific stiffness, high energy absorption on impact, and low thermal conductivity (1–40 W/mK). Besides that, metal foam is nonflammable, nontoxic, affordable, and recyclable. The mechanical properties of the standard aluminum foam alloys of Aluinvent (EN43100 and EN6061) are listed in Table 1. All values of the aluminum foams are average values and calculated from compression curves measured by 100 kN Instron or 100 kN Hegewald universal testing machines. The evaluation of the data is based on the DIN 50134 standard. The two alloys melt in different solidus (Ts) and liquidus (Tl) temperatures. The EN 43100 alloy has Ts = 557 °C and Tl = 596 °C, and the EN 6061 has Ts = 582 °C and Tl = 652 °C solidus and liquidus temperatures, respectively.

Casting process. Aluminum foam casting or cast around is already investigated in the literature using low-pressure or high-pressure die casting and gravity casting [8, 9]. Besides the continuous casting process of ALUHAB production, certain ALUHAB aluminum foams can be casted in liquid form into two-dimensional (2D) (plate) or three-dimensional (3D) (shape) without disintegration of the structure or change in the bubble size [7]. The investigated car parts were made by high-pressure die casting (HPDC) of liquid aluminum around the solid aluminum foam cores at OMEN Die Casting Ltd. using AC 46000 (EN 1706, Ts = 574 °C, Tl = 582 °C) aluminum alloy employing Buhler Evolution 53/D die-casting machine. EN 43100 (lot number F139 with density of 0.6 g/cm³) and EN 6061 (lot number F155 and F144 with density of 0.9 g/cm³) alloys were selected for the foam cores. The cast parts can be seen in Figure 1a. During the high-pressure die casting, the aluminum foam core (Figure 1b) was inserted into a casting machine (Figure 1c) and it was cast around with the conventional casting method using moderate parameters. Usually, the high-pressure die casting pressure is between 400 and 1200 bar and the plunger speed is between 1 and 6 m/s. We have selected the lower 400–600 bar pressure range and 1.5–4.5 m/s plunger speed range.

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The influence of the foam core types and the casting parameters (the plunger speed and the casting pressure) of the die filling on the casting prototype quality is shown in Table 2.

### 3. Properties of ALUHAB

**Morphological analysis.** The ALUHAB aluminum foams have homogeneous cell structure with certain density and cell size. To characterize the produced aluminum foams, micro-CT measurements were carried out to acquire the 3D data sets of the cell size distributions. A microfocus X-ray source and a flat panel detector by Hamamatsu were used for imaging. Aluminum foams were measured applying 100 kV acceleration voltage, 110 μA current, and 5 μm spot size to get an optimum exposure time–resolution ratio. The 10 × 10 × 10 mm³ size ALUHAB cubes were placed on a motor rotating sample holder to make the 2000 projections in 360° rotation with 700 ms exposure time.

### Table 1. Properties of EN43100 and EN6061 alloys based standard aluminum foams of Aluinvent [7]

| Type   | Cell size, mm | Density, kg/m³ | Relative density, % | Compressive strength, MPa | Specific energy absorption, kJ/kg (20%) | Specific energy absorption, kJ/kg (50%) | Volumetric energy absorption, MJ/m³ (20%) | Volumetric energy absorption, MJ/m³ (50%) |
|--------|---------------|----------------|---------------------|---------------------------|----------------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|
| AF100  | 12            | 100            | 3.7                 | 0.2                       | 0.3                                    | 1                                      | 0.03                                     | 0.10                                     |
| AF200  | 5             | 200            | 7.4                 | 0.5                       | 0.5                                    | 1.7                                    | 0.10                                     | 0.34                                     |
| AF300  | 3             | 300            | 11.1                | 2                         | 1.2                                    | 3.8                                    | 0.4                                      | 1.1                                      |
| AF400  | 2             | 400            | 14.8                | 4                         | 2.0                                    | 5.9                                    | 0.8                                      | 2.4                                      |
| AF500  | 1.5           | 500            | 18.5                | 6                         | 2.7                                    | 7.9                                    | 1.4                                      | 6.0                                      |
| AF600  | 1             | 600            | 22.2                | 11                        | 3.4                                    | 10.0                                   | 2.0                                      | 8.5                                      |
| AF700  | 1             | 700            | 25.9                | 15                        | 4.1                                    | 12.1                                   | 2.9                                      | 9.0                                      |
| AF800  | 1             | 800            | 29.6                | 20                        | 4.8                                    | 14.2                                   | 3.8                                      | 11.4                                     |
| AF900  | 1             | 900            | 33.3                | 25                        | 5.5                                    | 16.3                                   | 5.0                                      | 14.7                                     |
| AF1000 | 1             | 1000           | 37.0                | 30                        | 6.2                                    | 18.3                                   | 6.2                                      | 18.3                                     |

### Table 2. Influence of the foam core types and the casting parameters on the casting prototype quality

| ID   | Foam density, g/cm³ | Alloy     | Plunger speed, m/s | Casting pressure, bar | Deep infiltration of Al into the foam | Foam partially washed away | Pores in the HPDC skin |
|------|---------------------|-----------|--------------------|----------------------|--------------------------------------|---------------------------|------------------------|
| 1    | 0.9                 | EN6061    | 1.5                | 400                  | No                                   | No                        | Yes                    |
| 2    | 0.9                 | EN6061    | 2                  | 600                  | No                                   | Yes                       | No                     |
| 3    | 0.9                 | EN6061    | 3.5                | 400                  | No                                   | No                        | Yes                    |
| 4    | 0.9                 | EN6061    | 4                  | 400                  | No                                   | Yes                       | Yes                    |
| 5    | 0.9                 | EN6061    | 4.5                | 450                  | No                                   | Yes                       | Yes                    |
| 6    | 0.9                 | EN6061    | 4                  | 500                  | No                                   | Yes                       | Yes                    |
| 7    | 0.6                 | EN43100   | 4                  | 500                  | No                                   | Yes                       | Yes                    |
| 8    | 0.9                 | EN6061    | 4                  | 500                  | No                                   | Yes                       | Yes                    |
| 9    | 0.6                 | EN43100   | 2                  | 400                  | No                                   | Yes                       | Yes                    |
| 10   | 0.6                 | EN43100   | 4                  | 400                  | No                                   | Yes                       | Yes                    |
| 11   | 0.9                 | EN6061    | 4                  | 400                  | Yes                                  | No                        | No                     |
| C    | 0.6                 | EN43100   | <4                 | <500                 | No                                   | Yes                       | Yes                    |
| 1A   | 0.9                 | EN6061    | 3.8                | 500                  | No                                   | No                        | No                     |
| R    | 0.9                 | EN6061    | 1.5                | 500                  | No                                   | No                        | No                     |

Figure 1. High-pressure die casting with aluminum foam core, (a) car part, (b) solid aluminum foam core, and (c) aluminum foam core inserted into the casting machine.

Figure 2. (a) CT slice of an ALUHAB foam sample (EN43100 alloy, lot number F139, 10 × 10 × 10 mm³ volume), (b) 3D tomography reconstruction image of the foam, and (c) cell size volume distribution.
The cone beam reconstructions were made by an Octopus 8.7 software from the previously prepared projections.

Image analysis of the 3D tomography images was performed with self-made software provided by Wigner Research Centre for Physics. The software applies binarization and segmentation steps, and then, the cell size distribution can be calculated. Figure 2c shows the volume histogram with a distinct peak of 0.84 mm which demonstrates the average cell size and the homogeneity.

Mechanical properties of aluminum foam cores.
Compression tests were applied to the same foams used in the casting trials. The strength of the two aluminum foams EN 43100 (lot number F139 with density of 0.6 g/cm$^3$) and EN 6061 (lot number F155 with density of 0.9 g/cm$^3$) was determined in order to set the maximum pressure applicable during die casting. After cutting the foams to $40 \times 40 \times 40$ mm$^3$ cubes, the compression tests were carried out by a 100 kN Instron machine at a rate of 10 mm/min. The aluminum foam made from EN43100 composite with 0.6 g/cm$^3$ density has around 12 MPa compressive strength, and the EN 6061 composite foam with 0.9 g/cm$^3$ density has around 25 MPa compressive strength (Figure 3).

4. 3D tomography measurements of the aluminum foam cored die cast car parts

Computed tomography measurements were made on the aluminum foam cored die cast car parts. Because of the larger size of the parts, to acquire optimal reconstructions, higher acceleration voltage and higher current were used during recording of the projections. Thus, the tomograms were made by 110 kV voltage and 200 μA current. All of the other parameters were the same as the measurements of the ALUHAB cores (see Section 3). To investigate the effect of the casting parameters, i.e., pressure, plunger speed, and the foam material, several experiments were made (Table 2). The CT measurements of the car parts provided a feedback to the process of the die casting. Figure 4 shows two relevant results where the influence of the foam insert material on the product quality can be seen.

The optimization of the structure of the foam core and the casting method resulted in the production of such complex parts where the two materials, the foam insert and the aluminum shell, are well integrated. The EN6061 aluminum foam core has higher melting range than the EN43100 and also higher melting range than the HPDC aluminum alloy (EN 1706); thereby, it resists against the partial melting and does not wash away during the die casting. Vicario et al. [9] proved that aluminum foams (density above 0.55 g/cm$^3$) can withstand 40 MPa (400 bar) injection molding pressure without mechanical disintegration. The lack of cracks on the CT images justified that our foams were strong enough to withstand 500 bar of the EN43100 foam and 600 bar of the EN6061 foam cases, respectively. Due to the close melting range of the casting alloy and
the EN43100 foam, the casting around of the EN43100 foams resulted wash away failure in all cases. If 500 bar or less casting pressure was applied of the EN6061 foams, penetration was not observed (Table 2). For understanding better the interlayer and the liquid aluminum penetration process to the foam core, computed tomography measurement was made on a cutout block of the cast part. The CT slices are shown in Figure 5. In the case of 500 bar casting pressure, the melt could not penetrate partially into the foam structure (see Figures 5 and 6). When the pressure further increased, deep penetration occurred (sample ID 2, in Table 2). The breaching points are clearly visible where the molten aluminum can penetrate into the empty cells. This penetration most probably depends on the local cell wall thickness and the turbulence of the liquid aluminum.

Some local breaching effect and the connection between the foam insert and the aluminum shell can be seen in Figure 6.

5. Summary

High-pressure die-cast aluminum car parts having aluminum foam core insert were produced and investigated with nondestructive X-ray micro-tomography measurements. From the CT images, the cell size distribution, the foam structure, and the interface of the bulk and the aluminum foam were characterized. In the case of higher melting point of alloys of the aluminum foam cores, sufficient connection was achieved between the foam and the bulk skin. In order to produce pore-free skin in the case of the EN6061 foam trials, higher casting pressure and low plunger speed (sample ID 2, in Table 2) were set. If both values were too low, pores remained in the bulk layer (sample ID 1 in Table 2). Due to the similar melting range of the EN43100 alloy aluminum foam and the casting alloy, the casting melt partially washed away the foam structure in all cases. The selection of the proper composition (strength and melting range) of the foam core and the casting parameter resulted in a complex lighter car part where the two materials, the foam insert and the aluminum shell, are well-defined and perfectly interconnected.

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References

1. Akiyama, S.; Ueno, H.; Imagawa, K.; Kitahara, A.; Morimoto, K.; Nishikawa, T.; Itoh, M. US Pat. 4 713 277, 1987.
2. Baumeister, J.; Schrader, H. US Pat. 5 151 246, 1992.
3. Jin, I.; Kenny, L. D.; Sang, H. US Patent 4 973 358, 1990.
4. Ruch, W. W.; Kirkevag, B. WO Pat. 9 101 387, 1991.
5. Leitmeier, D.; Degischer, H. P.; Flankl, H. J. Adv. Eng. Mater. 2002, 4, 735–740.
6. Babcsan, N.; Beke, S.; Makk, P.; Szamel, Gy.; Kadar, Cs. Procedia Mater. Sci. 2014, 4, 121–126.
7. Babcsan, N.; Beke, S.; Makk, P.; Szamel, G.; Kadar, C. Pilot production and properties of ALUHAB aluminum foams, 8th International Conference on Porous Metals and Metallic Foams, Metfoam 2013, Procedia Mater. Sci. 2014, 4, 121–126.
8. Bauer, B.; Kralj, S.; Busic, M. Tehnički vjesnik 2013, 20, 1095–1102.
9. Vicario, I.; Crespo, I.; Plaza, L. M.; Caballero, P.; Idoiaga, I. K. Metals 2016, 6, 24.