Metals **2015**, *5*, 1553-1565; doi:10.3390/met5031553

OPEN ACCESS

metals

ISSN 2075-4701

www.mdpi.com/journal/metals/

Review

New Approaches to Aluminum Integral Foam Production with Casting Methods

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Academic Editor: Hugo F. Lopez

Received: 25 June 2015 / Accepted: 21 August 2015 / Published: 28 August 2015

Abstract: Integral foam has been used in the production of polymer materials for a long time. Metal integral foam casting systems are obtained by transferring and adapting polymer injection technology. Metal integral foam produced by casting has a solid skin at the surface and a foam core. Producing near-net shape reduces production expenses. Insurance companies nowadays want the automotive industry to use metallic foam parts because of their higher impact energy absorption properties. In this paper, manufacturing processes of aluminum integral foam with casting methods will be discussed.

Keywords: aluminum; metal; foam; casting

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1. Introduction

Aluminum integral foams have wide applications in different industries because of their low density and high impact absorption [1,2], localized densification on impact [3,4], and lower thermal conductivity [5]. They are divided into two groups according to their structure [6,7]: open cell and closed cell. Different applications of metal integral foam have led to the development of various production methods.

The major advantage of metal foams produced by casting over other methods is the shell-like skin at the outer surface and the mostly closed cell foam inside the structure (Figure 1) [8]. Cast metal foams are preferred because of their physical and mechanical properties, especially their corrosion resistance and low thermal conductivity, and for their applications in the aerospace and automotive industries. Other important properties of cast-metal foams are a high stiffness to weight ratio, low density, fracture resistance, 10-times-greater impact energy absorption, acoustic isolation, direct flame resistance, and biocompatibility [9–12].

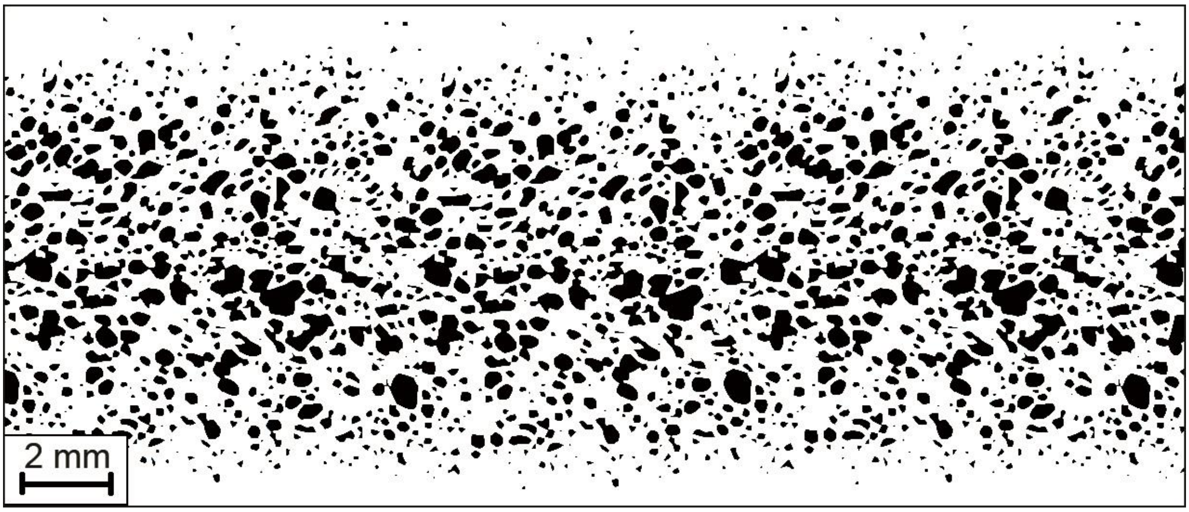

Figure 1. Skin and foam structure of aluminum integral foam produced by casting.

2. Aluminum Integral Foam Casting

The development of metal foam production started in the 1960s. The process could not satisfy the price expectations at that time. However, many researchers remained interested and metallic foams and casting systems are still research interests today [13–21]. Aluminum metal foam production is divided into two types: open cell and closed cell [6,7]. Production systems affect the aluminum metal foam's grain size, pore or cell size and shape, amount of pores, and shell thickness [7,11,22]. Thus, production has a major influence on the properties of the final product [23]. The amount of pores varies from 5%–97%, depending on the production method. Casting prototypes of metal foams and analytical solutions can be found in the literature [9,24–32]. There are also melt-squeezing procedures in the literature for metal foam production [33,34], but this technique is not included in this review.

There are a number of gas source types for metal foam production. The same gas sources are used to obtain cell structures in different casting systems as in other foam production systems: gas agents (e.g., TiH_2, MgH_2, $CaCO_3$, or $CaMg(CO_3)_2$), precursors, gas pressure chambers, or blowing gas into the melt with a nozzle [9,25,35,36]. The foamability of aluminum alloys depends on viscosity and cooling conditions [37]. The drainage period of liquid through the cell walls starts after the period of gas production. Drainage is affected by the viscosity and the surface tension of liquid metal and causes cells to collapse, shape defects, and non-uniform distribution of solid metal. Melt viscosity is enhanced by adding second phase ceramic particles such as SiC, Al_2O_3, or MgO [9,38–44].

Companies producing aluminum metal foams with different methods also have casting system prototypes. Some of the companies and their process names are Cymat (using the Alcan process; Mississauga, ON, Canada), Mepura (trade name Alulight; Ranshofen, Austria), Shinko Wire (trade name Alporas; Osaka, Japan), and ERG (trade name Duocel; Oakland, CA, USA).

In this paper, some of the prominent casting systems in the literature are explained.

2.1. Gas Sources of Metal Foam Production Systems

2.1.1. Gas Agents

Generally, $CaAl_2O_4$, ZrH_2, $CaMg(CO_3)_2$, TiH_2, and MnO_2 are used as gas agents for Al alloys. There are different gas agents for other alloys [45–47].

After the gas agents are decomposed, a gas is produced by the decomposition reaction. Every gas agent has its own reaction temperature (Equations (1)–(7) in Table 1), which also affects the liquid metal composition after being decomposed.

Table 1. Examples of gas agents used in metal foam systems.

Equation Number	Equation	Temperature
1	$TiH_2 \rightarrow Ti + H_2$	at 480 °C [48]
2	$nH_2O + mM \rightarrow M_mO_n + 2nH$	[49]
3	$MgCO_2 \rightarrow MgO + CO_2$	at 1300 °C [46]
4	$SrCO_2 \rightarrow SrO + CO_2$	at 1300 °C [46]
5	$CaCO_2 \rightarrow CaO + CO_2$	at 830 °C [50]
6	$2Al_{(l)} + 3CO_{2(g)} \rightarrow Al_2O_{3(s)} + 3CO_{(g)}$	[51]
7	$8Al_{(l)} + 3CO_{2(g)} \rightarrow 2Al_2O_{3(s)} + Al_4C_{3(s)}$	[51]

Equations (6) and (7) (Table 1) show that there could be other chemical products like Al_4C_3 in Equation (7) instead of CO in Equation (6), even if we want to have gas produced by the decomposition reaction while using the same gas agents as a gas source [51].

2.1.2. Precursor Gas Tablets

Precursors have been used as gas sources in metal foam production and have been prepared with different technologies [52–57]. Precursors consist of foamable gas agents and metal powders. Foamable gas agents are also called blow agents.

Precursors are used to obtain foam by re-melting. Aluminum powders are mixed with gas agent powders by hot pressing, extrusion, or powder rolling for Alulight or Foam-In-Al processes [58]. Gas agents can be added to aluminum alloys in die-casting or ordinary crucibles, which is called the Formgrip process [59]. Precursors used for Thixocasting are produced by pre-compacting powder mixtures to billets and heating them to the semi-solid state [60]. Liquid aluminum is sprayed and deposited on the gas agents in the Osprey casting system. The precursor process consists of foamable precursor production for the next step of the metal foam production system [28,45,50,59].

An alternative method for precursor production is the equal channel angular pressing method (ECAP). Precursors consist of aluminum powders, aluminum scrap, foaming agents, and stabilizing particles (oxides, calcium). Early decomposition of foaming agents can be overcome by preheating the precursor, which postpones the decomposition of gas agents and leads to using the ideal amount of the foaming agent [28].

2.1.3. Decomposition of Moisture from Mold Surfaces

Suematsu proposed the pore evolution model with moisture [36]. Absorbed moisture on the surface of the mold is decomposed into hydrogen and oxygen in the casting. Metal is oxidized and hydrogen is absorbed in molten metal. Absorbed hydrogen forms pores while the metal is solidifying because of temperature-dependent insoluble hydrogen. The temperature dependence of hydrogen solubility in solid and liquid aluminum under the hydrogen pressure of 0.1 Mpa is given in Table 2 [49]. This production is the same as lotus metal production [38]. Oxygen from the moisture decomposition forms oxides that are heterogeneous nucleation centers. Thus, more pores can be obtained with moisturized mold surfaces than dry molds with the same amount of hydrogen gas concentration in molten metal obtained in a gas pressure chamber [49].

Table 2. Molar fraction of hydrogen atoms (MFH) in aluminum according to temperature [49].

Equation Number	Equation	Temperature Range/K
1	$\mathrm{MFH} = 4 \times 10^{-9} \times e^{0.006T}$	675–938
2	$\mathrm{MFH} = 4 \times 10^{-13} \times e^{0.320T}$	938–946
3	$\mathrm{MFH} = 1 \times 10^{-7} \times e^{0.005T}$	946–1140

2.1.4. Direct Gas Injection

The device consists of a gas blower and impeller. Pore formation gas is introduced to the liquid metal with a tube while the impeller rotates in liquid metal. The impeller is rotated at 600–800 rpm. Gas pressure is applied to the gas chamber for foam production and the gas rate is 6–7 L/min [61]. Uniform distribution of the pore and refined size can be obtained from the system.

2.2. Aluminum Foam Casting Methods

2.2.1. Mold Casting

Gas agents are unnecessary in this aluminum metal foam casting system. The gas pressure inside the liquid metal is obtained by controlling the gas pressure of the casting chamber (Figure 2). The gas type is determined by the liquid metal. Hydrogen gas is used for aluminum and its alloys [24].

Directional solidification takes place in shell castings. Thus, gas bubbles form parallel to the direction of solidification. A chiller can also be applied to the cylindrical side face of the mold. Thus, sides of the casting become cooler. This leads gas bubbles to form from the outer surface of the metal toward the center. The development of the side cooling system guides continuous casting for metal foam production [49–63].

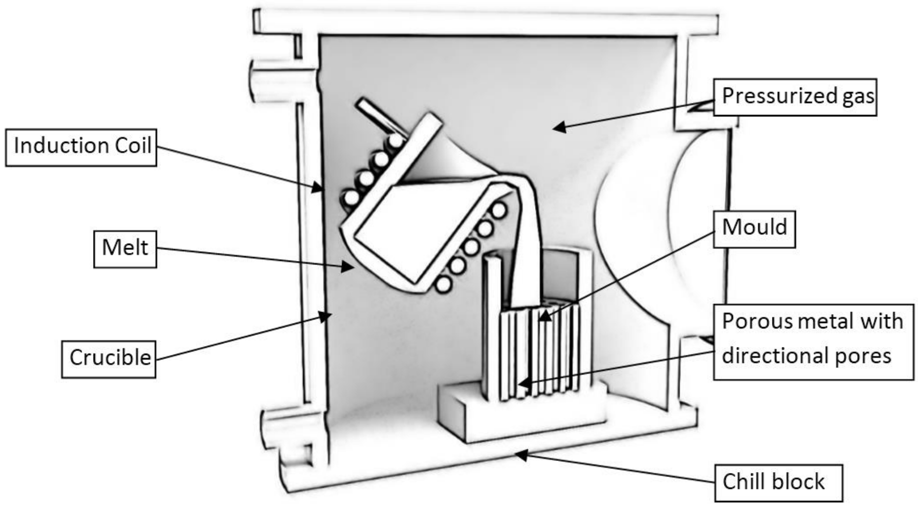

Figure 2. Mold casting system for production of metal foam [49].

2.2.2. Continuous Casting

The melting unit, mold, and cooler are placed in a gas chamber. The gas concentration inside the liquid metal is adjusted by gas pressure in the chamber. The production method is similar to standard continuous casting.

Cells form with the dissolved gas in the liquid metal during solidification. Cell formation is explained by porosity. Parameters affecting porosity affect the cell formation, too. There is no need to use gas agents in this type of metal foam production (Figure 3) [49,57,61].

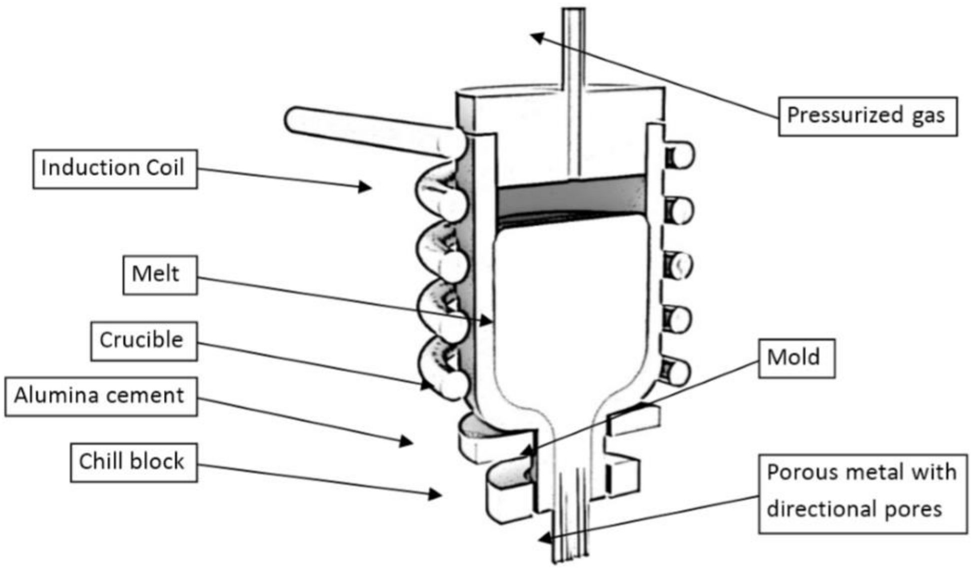

Figure 3. Integral aluminum foam production with continuous casting [49,61].

2.2.3. Investment Casting and Evaporative Pattern Casting

Metal foams can also be produced by investment casting. Open cell polymer foams are produced from polyurethane materials. The polymer foam is impregnated with a heat-resistant resin. This system is used as a space holder.

The polymer foam is removed from the system by heat, in the same way the wax is removed in investment casting. The space will be filled with casting metal after the polymer is removed from the system, as shown in Figure 4.

The mold is heated to aid filling, especially the narrow areas, before the casting. Open cell metal foam is produced by pressure investment casting. The commercial names of the production methods are DUOCEL and Cellmet; 6101 and A356 aluminum alloys are produced by this method [9,27,38,57,64,65].

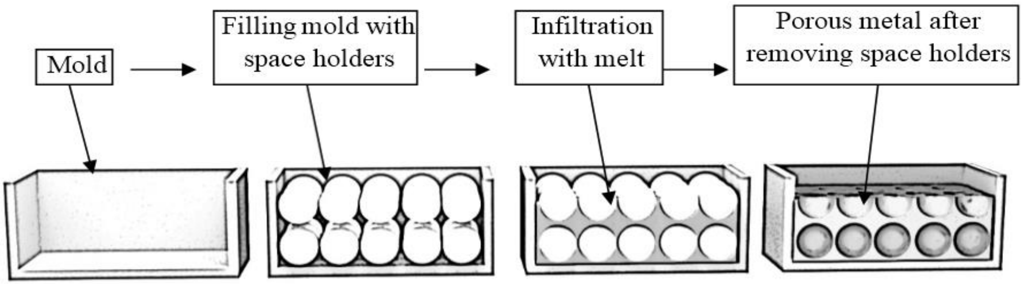

Figure 4. Production of aluminum metal foams using space holders [38,57,64].

2.2.4. Casting with Precursor Gas Tablets

Precursor gas tablets are made of a mixture of aluminum powders and TiH_2 powder and are processed by ECAP. The ECAP process replaces the steps with cold isostatic pressing of powder and gas agent mixtures and extrusion. The benefits of the system are no pre-compaction, no preheating of powders, and continuous and almost scrap-free production. This method reduces manufacturing costs by about 70% because lower amounts of gas agents are necessary. Pouring melt on the precursor gas tablets will lead to foaming (Figure 5). Melt is a heater for precursor gas tablets and fills the space between precursor gas tablets [28].

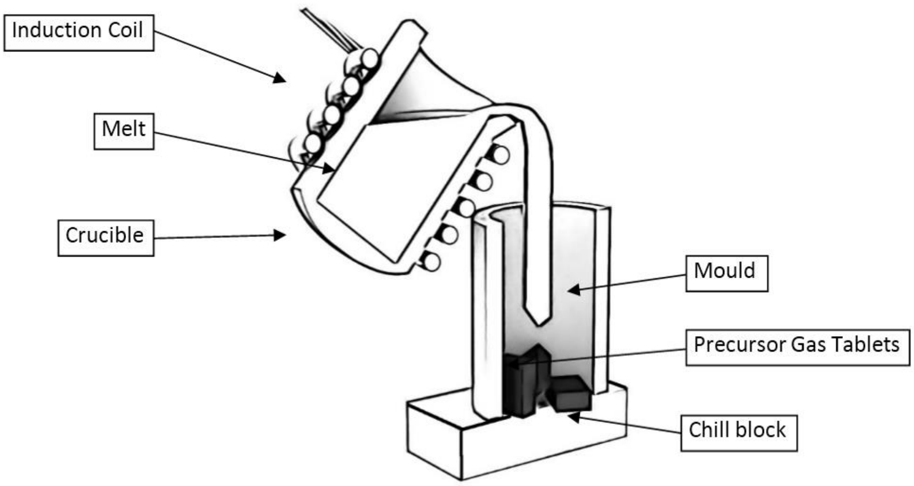

Figure 5. Casting aluminum on foamable precursor gas tablets [28].

2.2.5. Direct Foaming Investment Casting

The direct foaming of melts by direct gas injection is used for producing foam in 6–7 mm thick ceramic shell molds, which are produced from zircon and molochite refractories used for casting [66].

Carbide particles are mixed with the impeller in the melt. Pressurized air is applied to the impeller's air input for the desired amount of foaming. Foam will fill the crucible first and then flow to the sprue (Figure 6). After filling the sprue with foam, the impeller rotation is stopped. The mold is removed from the crucible after 20 s so the foam will solidify [66].

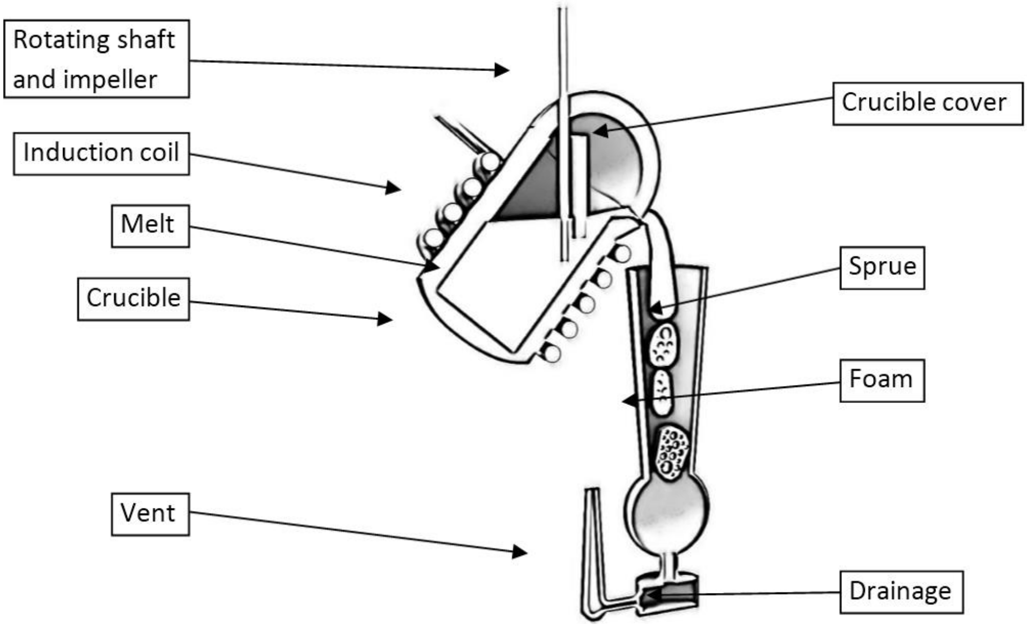

Figure 6. Casting configuration showing direct foaming investment casting [66].

The surface quality of the product could be improved by higher casting temperatures. However, this will increase both the amount of drained metal and the density of the product. The range of product density is higher than with other production methods. The reason is probably because extra liquid metal carried with foam to the sprue and non-drained liquid metal remains on cell walls. Another reason could be the bursting of some of the bubbles during the filling of the sprue by foam [67] and the increase in the density [66].

2.2.6. High Pressure Integral Foam Moulding (HP-IFM)

The melt is injected into a steel mold under standard die-casting conditions with high velocity. A high dwell pressure of several hundred bars is applied after the mold has been filled completely. The filling time period is the same as in conventional die-casting aluminum production. Liquid metal that fills the mold cannot expand between 10–150 milliseconds due to the decomposition of the gas agents. After this period, liquid metal starts to expand, and compared to the standard die-casting method, the expansion time is longer but the pressure is too high. Gas agents are added to the liquid metal as a powder in between the injection cylinder and part cavity. MgH_2 and TiH_2 are widely used as gas agents. The dissolution time and the temperature of gas agents are important parameters for choosing the right agent. Gas agents that are present in the liquid metal start to increase the pressure of the gas in the mold [8,26].

Figure 7 shows that one of the mold parts is moveable to decrease the gas pressure in the mold. Moving the mold face will allow controlling the expansion of this integral metal foam in HP-IFM systems [26].

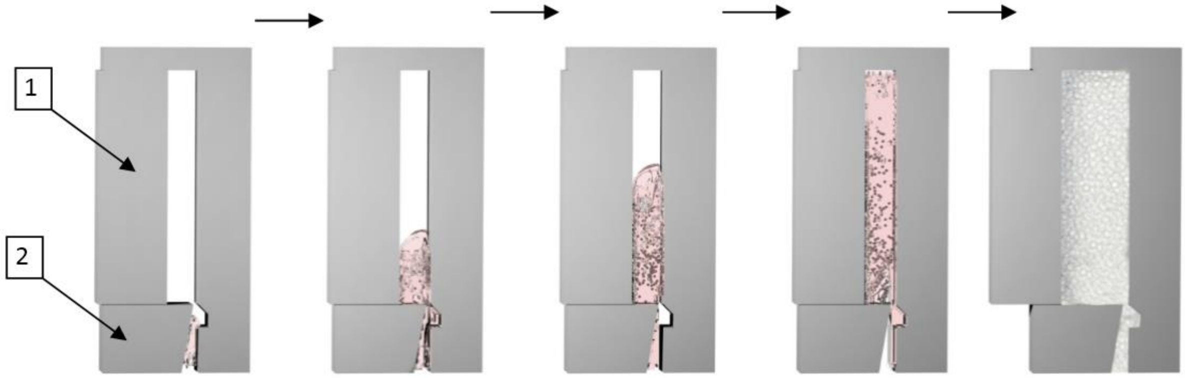

Figure 7. HP-IFM. Part 1 is moving and part 2 is stable [26].

Mechanical properties of different commercially produced aluminum metal foams are listed in Table 3. Foaming temperature and homogenizing heat treatment provide the desired mechanical properties [7,68,69].

Table 3. Aluminum metal foam's mechanical properties [27].

Properties	Cymat, Alcan	Mepura, Alulight	Shinko Wire, Alporas	ERG, Duocel
Materials	Al–SiC	Al–Mg–Si	Al–5Ca–Ti	Al 6061 T6
Relative density	0.02–0.2	0.1–0.35	0.08–0.1	0.05–0.1
Structure	Closed Cell	Closed Cell	Closed Cell	Open Cell
Young's Modulus [MPa]	0.02–2.0	1.7–12	0.4–1.0	0.06–0.3
Poisson's ratio, ν	0.31–0.34	0.31–0.35	0.31–0.36	0.31–0.37
Compression strength [MPa]	0.04–7.0	1.9–14.0	1.3–1.7	0.9–3.0
Tensile strength [MPa]	0.05–8.5	2.2–30	1.6–1.9	1.9–3.5
Fracture toughness [MPa $m^{1/2}$]	0.03–0.5	0.3–1.6	0.1–0.9	0.1–0.2
Thermal conductivity [W/m K]	0.3–10	3.0–3.5	3.5–4.5	6.0–11

2.3. Properties of Some of the Commercial Al Foams

Compressive stress-strain curves up to the densification strain are shown in Figure 8. The chemical composition, the foam cell wall shape and its curvature, the sample direction, the cell type (open or closed), and the uniform distribution throughout the depth of the product are important factors from the view-point of their mechanical properties. Sometimes these aluminum foams are called by company names or product names. The ERG and Alporas foams have an almost constant plateau stress with increasing strain until the densification occurs. The serrations of Alcan foam correspond to the fracture of the cell walls (Figure 8) [70].

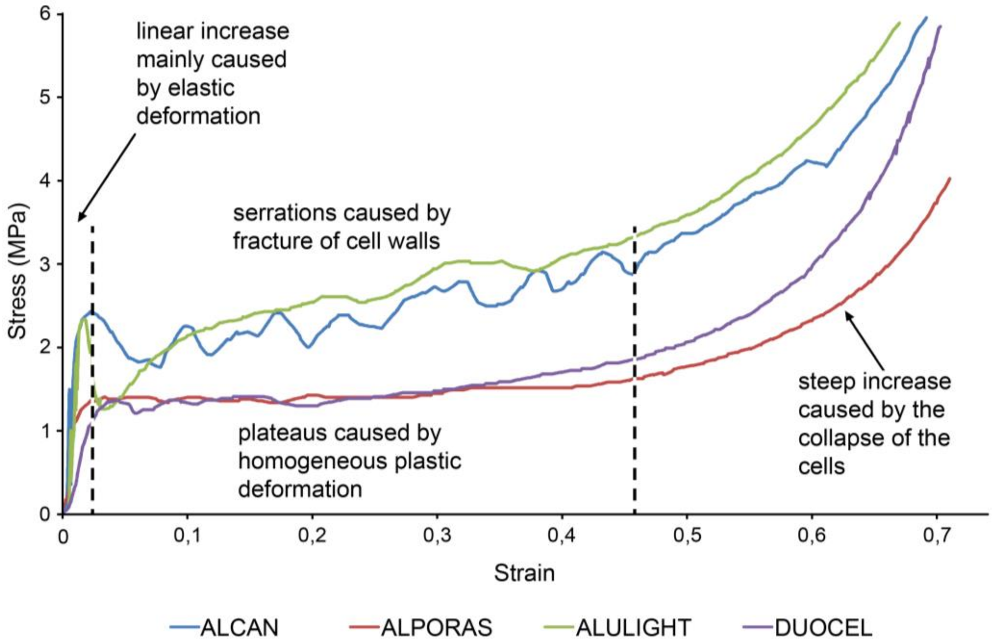

Figure 8. Compressive stress-strain curves for aluminum foams up to densification strain [70].

3. Results

Since aluminum foams have special advantages such as good heat resistance, higher strength, incombustibility, possibility for easy recycling, and sound and heat absorption, they can become an interesting material for applications in several branches of different industries.

The increasing use of metal foams has driven the development of a wide range of production methods. Low cost is an advantage of production by casting compared to other integral metal foam production methods of complex-shaped parts. The cost of quality metal foam production is high because gas agents are expensive. Different gas production and metal foam production methods are being developed to decrease the final product cost. The information obtained in the studies with gas and cell formation cannot fully explain pore formation, but a number of pore formation theories are available in the literature.

The gas present in liquid metal influences foam formation. Pore size will be larger if there is no particle added to the liquid metal. The porous structure can easily collapse due to the low viscosity of the liquid metal. Ceramic particles such as SiC, Al_2O_3, and MgO are added to increase viscosity. Thus, adding particles will stop liquid-metal drainage and collapsing pore walls during foaming. The formation will be negatively influenced if the particles exceed a certain amount.

Acknowledgments

This work was supported by Scientific Research Projects 2014.01.0152.001 and 2014.01.0152.002.

Author Contributions

All authors contributed equally to this work. A.G. and M.M.A. conducted the conception and design of the study. M.N. collected the information of different systems.

Conflicts of Interest

The authors declare no conflict of interest.

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