

Cold-chamber die-casting manufacturing and characterization of aluminum matrix syntactic foams

Péter SZALVA

szalva@eik.bme.hu

Budapest University of Technology and Economics

Ibolya KARDOS

Budapest University of Technology and Economics

Dóra KÁROLY

Budapest University of Technology and Economics

Anna SZIJÁRTÓ

Budapest University of Technology and Economics

Tamás BUBONYI

MTA–BME Lendület "Momentum" High-performance Composite Metal Foams Research Group

Tamás RICK

FÉMALK ZRt

Melissza ZSOLDOS

Budapest University of Technology and Economics

Alexandra KEMÉNY

Budapest University of Technology and Economics

Imre Norbert ORBULOV

Budapest University of Technology and Economics

Research Article

Keywords: aluminum, high-pressure die casting, ceramic hollow spheres, aluminum matrix syntactic foam, mechanical characterization

Posted Date: October 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10391924/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Cold-chamber die-casting manufacturing and characterization of aluminum matrix syntactic foams

Péter SZALVA^{1,2,3*}, Ibolya KARDOS¹, Dóra KÁROLY^{1,2}, Anna SZIJÁRTÓ⁴, Tamás BUBONYI^{2,5}, Tamás RICK³, Melissza ZSOLDOS³, Alexandra KEMÉNY^{1,2}, Imre Norbert ORBULOV^{1,24}

¹Department of Materials Science and Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rakpart 3., H-1111, Budapest, Hungary

²MTA–BME Lendület „Momentum” High-performance Composite Metal Foams Research Group, Műegyetem rakpart 3., H-1111, Budapest, Hungary

³FÉMALK ZRt., Öntöde utca 2-12., H-1211, Budapest, Hungary

⁴Department of Construction Materials and Technologies, Faculty of Civil Engineering, Budapest University of Technology and Economics, Műegyetem rakpart 3., H-1111, Budapest, Hungary

⁵Institute of Physical Metallurgy, Metalforming and Nanotechnology, University of Miskolc, Egyetemváros C/1, H-3515, Miskolc, Hungary

*Corresponding Author: szalva@eik.bme.hu

*Telephone number: +36-30-327 3014

*ORCID ID: 0000-0002-6562-6165

Keywords: aluminum, high-pressure die casting, ceramic hollow spheres, aluminum matrix syntactic foam, mechanical characterization

Abstract

Axisymmetric (near cylindrical) AlSi9Cu3(Fe) aluminum matrix syntactic foam (AMSF) uniaxial compression test samples were cold-chamber die cast in a two-cavity mold with a minimum wall draft (2°) suitable for ejection from a die cavity, where the C795 Al₂O₃ hollow sphere fillers were pre-fixed. To produce AMSFs by high-pressure die casting without complex, large-scale tools, it is essential to bond the filler materials into a predefined geometry that can be placed into the die tool. The cold chamber die cast AMSFs were characterized for density, investigated (micro)structurally via computed tomography, optical- and scanning electron microscopy (extended by energy-dispersive X-ray spectrometry). The mechanical properties of the cast AMSFs were investigated using uniaxial compression tests and evaluated in accordance with ISO 13314. During the uniaxial compression test, the Al₂O₃ hollow spheres effectively collaborated with the AlSi9Cu3(Fe) matrix. The space between the hollow spheres was completely filled with the matrix, and the hollow spheres did not begin to fill or collapse during casting. As characteristic mechanical properties, the compressive strength, the plateau strength, the energy absorption and the specific energy absorption at 0.5 deformation were measured to be $\sigma_c = 151.1 \pm 10.4$ MPa, $\sigma_{pl} = 99.1 \pm 12.8$ MPa, $W_{0.5} = 51.1 \pm 5.0$ Jcm⁻³ and $SEA = 25.7 \pm 2.0$ Jg⁻¹, respectively, at an average bulk density of 2.05 ± 0.12 gcm⁻³. These findings demonstrate that die casting provides a technically feasible route for the industrial-scale production of aluminum matrix syntactic foams while preserving excellent filler integrity and competitive mechanical performance.

1. Introduction

The ongoing development of metal matrix syntactic foams (MMSFs) aims to produce lightweight structures suitable for the competitive industry. They either reduce material costs by using low-cost filler particles, such as expanded glass [1–3], lightweight expanded clay aggregate particles [4–7], pumice [8] or other ceramic particles with porous inner structures [9–12], which usually results in lower strength and energy absorption. The lower strength of the fillers can be equalized by the proper choice of matrix materials, such as precipitation hardening aluminum alloys [13–15], magnesium alloys [16–18], zinc alloys [19,20], or steel [21–24]. Another approach to reducing costs is to streamline and simplify the manufacturing process. So far, this has been achieved primarily by melting the matrix material and producing MMSFs via stir casting [1,25,26] and manual infiltration techniques [1,22,27–29]. Additional simplification lies in the development of in-situ foam-filled tubes [30–34], which reduces the number of production steps. However, no progress has been made yet toward automation or large-scale manufacturing, leaving a significant research gap between laboratory-scale experiments and mass production.

In recent years, the field of mechanical engineering has witnessed significant advancements in the development and application of innovative materials and manufacturing technologies. Among the latter, high-pressure die casting (HPDC) has emerged as a highly efficient method for the mass production of complex metal components, playing a pivotal role, particularly in the automotive, aerospace, and electronics industries [35–37]. HPDC enables the production of parts with complex geometries, reliable dimensional accuracy, and good surface quality, all of which are essential requirements in modern engineering applications [38–40].

Aluminum alloys are among the most widely used materials in pressure die casting [41]. Its unique combination of lightweight characteristics, high strength-to-weight ratio, and outstanding corrosion resistance makes it an ideal candidate for a broad range of applications [42]. Parallel to advances in die casting techniques, metal foams represent another remarkable innovation in materials engineering. MMSFs, particularly those based on aluminum, possess a unique cellular structure characterized by a high pore volume fraction, leading to relative densities of $\sim 0.4 - 0.6$ [43,44]. The essence of the problem of selecting the optimal matrix alloy is that when choosing the matrix material, several - often conflicting - aspects (strength, corrosion resistance, cost, castability, reinforcement compatibility, etc.) must be considered simultaneously. A natural and highly ranked choice is the cast aluminum alloys [45]. During their selection, the goal was not only to meet the material requirements but also to ensure cost-effective manufacturability [46–48]. High-performance, lightweight materials in aerospace, automotive, and structural applications have generated significant interest in aluminum-based metal matrix composites. However, one can assume that the process of adding a reinforcement to the matrix alloy for HPDC needs some improvement. The aim is to overcome the agglomeration and the non-homogeneous distribution [49]. Another investigation also states that aluminum matrix syntactic foams (AMSFs) can be manufactured in an industrial environment using cold chamber low-pressure die casting (LPDC). The process choice aims to avoid undesirable chemical reactions at the aluminum (matrix) – silica (filler) interface due to relatively rapid cooling [14]. The process results in excellent infiltration even in narrow gaps between the individual fillers. The main results are that (i) the filler particle size plays a key role in the mechanical behavior, and (ii) bimodality reduces filler collapse and leads to more uniform density [10].

Intensive cooling is another key benefit of HPDC. For instance, the effect of cooling rate on the microstructure and mechanical properties of the AlSi9Cu3(Fe) alloy was investigated [50]. Increasing the cooling rate significantly refines the microstructure: the secondary dendrite arm spacing (SDAS) decreases, the spatial and size distributions of eutectic silicon become homogeneous, and the

distribution of intermetallic phases becomes more uniform. The faster cooling is key to reducing the size of the brittle, needle-like iron-containing intermetallics and their harmful effects. Through their effective control, the mechanical properties improved significantly. In summary, the mechanical performance of the AlSi9Cu3(Fe) alloy is determined by its microstructure, which is heavily influenced by the cooling rate. Therefore, it is essential to control cooling conditions to ensure casting quality and optimize properties. The effect of cooling rate has been investigated from several aspects. The AlSi9Cu3(Fe) alloy modified with strontium and magnesium additions clearly formed several intermetallic phases (particularly coarse, hard Al₅FeSi needles), which caused embrittlement [51] in the case of gas pressure infiltration (GPI) technique. On the other hand, GPI includes a slow cooling process, resulting in a coarser microstructure, while in the case of HPDC, up to 60-125 K/s cooling rate is possible, which is extremely intensive and helps to tackle the problem.

Ceramic hollow spheres (CHSs) as space-filling materials provide a geometrically and functionally tuned material structure. From a foundry perspective, this means that mechanical performance is determined not only by alloy selection but also by control of local relative density. Non-optimized distribution deteriorates penetration resistance and mechanical properties [52]. It is vital that space-fillers are placed in a structured shape. Studies have investigated how alumina fillers affect the mechanical properties of aluminum foams for lightweight applications. They significantly increased compressive strength, plateau stress, and energy absorption. The stiff ceramic particles strengthen the cell walls, delaying local collapse. Energy absorption increases, but the fracture mode becomes more brittle, especially at higher alumina filler contents. Compression tests confirm that the effect of the fillers is primarily to mechanically reinforce the cell walls, with alumina fillers acting as a functional reinforcing constituent [53]. However, they also cause more brittle behavior at higher concentrations. In conclusion, the mechanical properties are determined not only by the amount of the filler, but also by its distribution and by the control of the manufacturing technology. The key to optimal results is strict control of the technological parameters [54].

The intersection of HPDC and metal foam technology opens new opportunities for engineers to design and fabricate advanced components that meet increasingly demanding performance specifications. The synergy between these two areas not only enables the large-scale production of lightweight and complex parts but also introduces novel functionalities that have the potential to redefine the boundaries of conventional material design. Accordingly, ongoing research continues to focus on optimizing process parameters, improving the mechanical properties of foamed structures, and exploring the full potential of metal foams in the die casting process [10].

This article aims to provide in-depth insight into recent developments and future perspectives in pressure die casting, with particular emphasis on aluminum and the unique advantages of metal foams. Collaborative efforts between academia and industry will accelerate these innovations, enabling practical implementation and effectively addressing real-world engineering needs. Embracing these advancements will not only optimize mechanical design but also contribute to environmental sustainability and economic viability in future engineering projects. However, it is not unique for researchers to bridge the gap between laboratory research and industrial use [14]. Our primary objective is straightforward: to ensure that AMSF is suitable for real industrial applications and that its technical content (mechanical properties) can be reproduced under large-scale industrial conditions. For example, it is vital to consider the repeatability criterion of the automotive industry, as well as economic and short production cycles. Large-scale industrial implementation is currently limited by size constraints, the complexity of manufacturing geometries, and post-processing difficulties. The research is now ready to move from the laboratory to real industrial applications.

In this study, an axisymmetric (near cylindrical) uniaxial compression test specimen was cast in a two-cavity mold with a minimal wall draft (2°) suitable for ejection from a die cavity, where the CHS fillers were pre-fixed. The present work was to establish an industrially applicable manufacturing route for AMSF via conventional cold-chamber high-pressure die casting to produce AMSFs by HPDC without the complexity of large-scale tools. The mechanical properties of the cast AMSFs were evaluated by uniaxial compression testing; their physical properties by weighing; their macrostructure by computer tomography (CT); and the relationship between the matrix and the filler material on cross-section by light optical microscopy (LOM) and scanning electron microscopy (SEM). Particular emphasis was placed on developing a pre-bonded CHS preform suitable for automated die-casting production and on evaluating the effect of the third-phase pressure on infiltration behavior, structural integrity, and compressive performance.

2. Materials and Methods

The die-cast specimens were cast in a two-cavity casting tool (Fig. 1). The casting die was specifically designed for uniaxial compression test specimens. The cast material was a widely used Al-Si-Cu secondary aluminum alloy, namely AlSi9Cu3(Fe) (EN AC 46000). The MMSF specimen set was cast from a single melt dose. The chemical composition of the cast was analyzed by using X-ray fluorescence (XRF) tabulated in Table 1. C795 grade, pure Al_2O_3 CHSs, produced by Hollomet GmbH (under the tradename globocer®) with an average diameter of $\varnothing 6.78 \pm 0.17$ mm and wall thickness of 0.344 ± 0.033 mm, were used as filler.

Table 1. Chemical composition of the AlSi9Cu3(Fe) matrix alloy (in wt%).

Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
9.85	0.75	2.55	0.31	0.30	0.70	0.10±	
± 0.1	± 0.2	± 0.2	± 0.3	± 0.2	± 0.2	0.04	balance

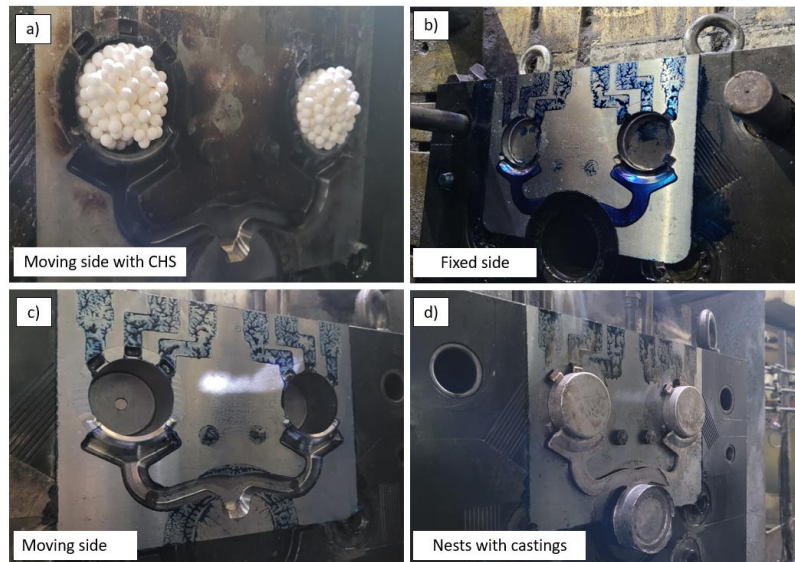


Figure 1. The casting die with inserted alumina sets (a), fixed side (b), and moving side (c), with empty cavities, and the moving side with a casting bunch (d).

The specimen was produced using an OMS 450 cold-chamber die-casting machine. The molten metal was degassed by gas-bubbling filtration (GBF) at 18 Lmin^{-1} (nitrogen for 5 min). The molten metal was

dozed automatically at 695°C melt temperature. The tool was preheated to 80°C. The temperature was maintained by water circulated at 90°C through a Tool-Temp TT-390/2 machine. The casting parameters were calculated using flow analysis, and the gating system was designed to achieve proper die filling while minimizing entrapped gas inclusions (Figs. 1b and 1c). The plunger speed was set to 0.20 ms⁻¹ in the first phase and to 3.50 ms⁻¹ in the second phase, respectively. The pressure of the third phase was used as the experimental parameter, ranging from 0 to 28 MPa (0 to 280 bar) with varying pressure steps. The plunger tip diameter was 70 mm, and the total air volume in the die tool chamber was 374 cm³, from which the total air volume in the die was 322 cm³. Although the die cavities were individually 161 cm³, the inserted CHS occupied some of this volume, which was accounted for in the filling simulations. The specimen dimensions are defined in Fig. 2. All specimens were tested in as-cast ('F') condition.

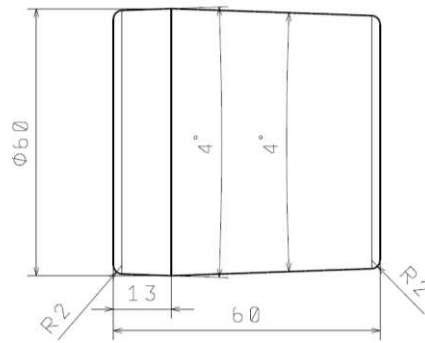


Figure 2. The design of the near-cylindrical uniaxial compression test specimen and its dimensions.

The shot chamber was 397 mm long, the switching point of the second phase was at 311 mm, and the same parameters were used in the simulation (Fig. 3.). The third phase switching point in the active shot chamber length was approximately 30 mm. When the cavity is completely filled with aluminum without CHS fillers (2×161 cm³), the casting bunch weighed 1305 g, which is 37 % of the chamber filling degree. Considering the CHS (~80 cm³ per cavity), the bunch weighed 920 g, corresponding to a chamber filling of 26%. Therefore, the amount of dosed metal was different during casting with CHS compared to the empty cavity.

The effect of the third phase pressure is minor in the simulation, but it must be set to a specific value, which was chosen as 24 MPa (240 bar). In the third phase, the volumetric shrinkage that occurs during the solidification of the metal is compensated for by the pressure, transferred to the metal through the piston. The metal pressure acting in the die cavity comes from the hydraulic pressure set in the shot cylinder and builds up in proportion to the plunger tip diameter and the hydraulic hammer diameter.

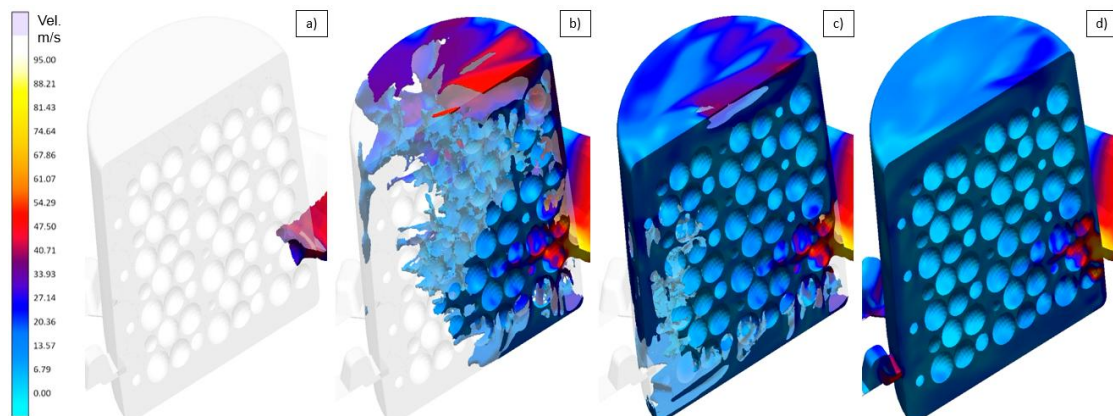


Figure 3. Images depicting the die-filling simulation.

Prior to casting, it is essential to bond the filler materials into a predefined geometry that can be placed in the die cavity. The bonding agent used during sample preparation was a 36 wt% aqueous sodium silicate solution ('waterglass', CAS 1344-09-8) produced by KEMIKÁL Ltd. (Budapest, Hungary), meaning that 100 g of solution contains 36 g sodium silicate and 64 g water.

To achieve the predefined geometry, a sample epoxy resin part was 3D-printed. The geometry of the printed part matched the die cavity, while its diameter and height were reduced by 2 mm and 4 mm, respectively. This reduction in volume was necessary to prevent the die cavities from being damaged during casting. The nominal diameter and height of the 3D printed part were both 56 mm. Measurements were taken at three positions using a caliper, yielding an average height of 57.22 ± 0.04 mm and an average diameter of 56.52 ± 0.16 mm.

The next step, namely the preparation of the bonded filler material (BFM), is illustrated in Fig. 4. The 3D-printed sample was covered with aluminum foil to obtain the determined die shape, which is further referred to as the holder (Figs. 4a and 4b). Subsequently, approximately 10 ml of waterglass was poured onto the required amount of filler material, which was then added to the holder to fill it, and the mixture was thoroughly stirred to ensure complete surface coating (Fig. 4c). In this way, the CHSs are spatially distributed in a random, closely packed system (~ 64 vol% filler volume fraction).

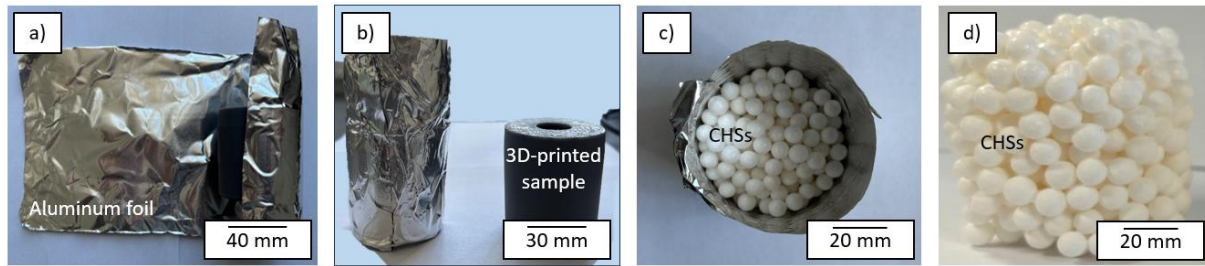


Figure 4. Bonded filler material preparation: (a) covering the 3D-printed sample with aluminum foil, (b) the prepared holder (the 3D-printed sample has already been removed), (c) waterglass-coated CHSs in the holder, and (d) bonded filler material (BFM, holder removed).

The most adequate heat treatment to harden the waterglass joints between the BFMs was determined based on the joint bridge diameter between the individual CHSs and the fracture force required to break the sets. According to these results, the prepared filler materials were heat-treated at 150°C for 5 h. One of the heat-treated BFMs is shown in Fig. 4d. The aim of the preliminary trials to find the best parameters above was to reduce the bond diameter to the minimum necessary (to keep the structural integrity of the set) while increasing the empty space the metal matrix can fill, thereby improving the expected mechanical properties of the produced MMSFs. During the production of the BFMs, special attention was given to maintaining the geometry and the dimensions of the sets. In the case of a BFM fracture, a broken piece may prevent the tool from closing properly or even damage the die, leading to manufacturing problems. In addition to the standard samples with random, closely packed CHS sets (as described above), BFMs were prepared with a higher filler volume fraction to investigate the effect of the maximum filler volume, referred to as maximum filler (MF) specimens. In this case, the almost identical diameter CHSs were situated manually, one-by-one, into the holder in a close-packed system (~ 74 vol% filler volume fraction). The produced sample castings and their tests are summarized in Table 2. The table contains the pressure values for the third phase and the number of pieces for each test, including mass measurement, uniaxial compression test, CT test, and microscopic examination of the cut.

Table 2. Design of Experiment (DoE)

Sample Mark	Remark	Pressure MPa (bar)	Investigation (pcs.)			
			Mass	Compression	CT	LOM/SEM
O	Std. BFM	0 (0)	each	3	1	1
A	Std. BFM	14 (140)	each	3	1	1
B	Std. BFM	18 (180)	each	3	1	1
C	MF BFM	20 (200)	each	3	1	1
D	Std. BFM	22 (220)	each	3	1	1
E	MF BFM	24 (240)	each	3	1	1
F	Std. BFM	26 (260)	each	3	1	1
G	Std. BFM	28 (280)	each	3	1	1

During the mass weighing, each test specimen was weighed and compared with pieces without CHS, from which the MMSF's mass change was calculated as a percentage (Eq. 1). The measured mass changes (Δm) in each case ($m_{\text{CHS_multi}}$) refer to the total average mass of the produced pieces (m_{solid}), which means 6-8 pieces per pressure level. The weighing scale was an Entris 6202-1S with ± 0.01 g accuracy produced by Sartorius Lab.

$$\Delta m (\%) = \frac{\bar{m}_{\text{solid}} - \bar{m}_{\text{CHS_multi}}}{\bar{m}_{\text{solid}}} \quad (\text{Eq. 1})$$

The CT measurements were performed on a YXLON FF35 μ CT at the 3D Lab of the University of Miskolc, Hungary. The tube voltage was 145 kV, the tube current was 200 μ A, and 1080 projections were acquired per measurement. The focus-to-object distance was 300 mm, and the detector-to-object distance was 1050 mm; therefore, the voxel size was 39.7 μ m. Furthermore, a 0.5 mm thick Cu sheet was used as a filter, and the detector had a 2 Hz frame rate. Reconstruction was performed with YXLON Reconstruction Workspace 1.4.4.0, and voxel manipulation and analysis were performed with VG Studio Max 3.3. After automatic surface determination, the foam-powder analysis module was used to calculate pores within the structure. For the merge threshold, the standard 5% overlap was used [55], excluding the border cells. The pores were then divided into volumes: CHS voids and unwanted shrinkage or gas pores, which were filtered based on sphericity and compactness values. The sphericity is a dimensionless shape parameter that describes how closely a detected void (e.g. a pore or inclusion) resembles a perfect sphere.

The specimens were inspected with light optical microscopy (LOM) and scanning electron microscopy (SEM). The LOM microstructural observations were carried out using an Olympus BX51M microscope. The LOM sample preparation included grinding with abrasive SiC papers with mesh sizes 180, 600, 1200, and finally polishing with diamond suspension (3 and 0.2 μ m) in 5 steps. Each grinding step took 6 minutes with 20 N of axial force and 120 min^{-1} in a clockwise. The specimen was etched using a reagent for color metallographic etching. The etchant consisted of 100 mL of distilled water, 4 g of potassium permanganate (KMnO_4), and 1 g of sodium hydroxide (NaOH). During the etching process, a thin precipitate layer forms on the specimen surface. The thickness of this layer depends on the chemical properties of the individual microstructural constituents. The fracture surfaces of the samples and the matrix-filler contact surface on the polished sample were studied using a Zeiss Evo MA10 SEM (Carl Zeiss AG, Oberkochen, Germany) at 20 kV. To evaluate the connection between the matrix material and the ceramic spheres, energy-dispersive X-ray spectroscopy (EDS) measurements were conducted on an EDAX Z2 module (EDAX Inc., Mahwah, NJ, USA) with 0.2 μ m resolution, 700 pA probe current, and a 500 nm spot size along a line.

The compressive properties of the die-cast AMSF samples were characterized in accordance with ISO 13314:2011 [56], a standard for cellular and porous metallic structures. For each applied third-phase pressure, three randomly selected specimens were compressed. The measurements were carried out at room temperature, between two flat compressive plates (without lubrication) with position control and a cross-head speed of $10 \text{ mm} \cdot \text{min}^{-1}$, corresponding to an initial strain rate of $2.78 \cdot 10^{-3} \text{ s}^{-1}$; therefore, quasi-static conditions. The specimens were compressed in an Instron 5989 electromechanical material testing machine equipped with a 600 kN load cell. The deformation was monitored during the measurement with timed captures of a Nikon D700 digital camera. The recorded force–displacement data were converted into engineering stress–engineering strain values. The former was determined from the measured force values, divided by the original maximum cross-section, while the latter was calculated as the ratio of the measured displacement and the original height of the specimens. The samples were compared based on their characteristic compressive properties, such as (i) the first compressive stress maximum, referred to as compressive strength (σ_c , MPa) corresponding to the crack initialization in the specimens; (ii) the plateau stress (σ_{pl} , MPa) determined as the average of the engineering stress values between 0.2–0.3 engineering strain; (iii) the energy absorption up to 0.5 engineering strain ($W_{0.5}$, Jcm^{-3}) calculated as the mathematical area under the engineering stress–engineering strain curve; and (iv) the specific energy absorption (SEA, Jg^{-1}), by normalizing the calculated energy absorption by the bulk density of the corresponding specimen.

3. Results and Discussion

3.1. Physical properties

According to the testing of the BFMs with 28 standard and 12 MF specimens, the average weight was $65.52 \pm 6.03 \text{ g}$ and $77.14 \pm 4.19 \text{ g}$, respectively. Subsequently, the volume of water displaced by the BFMs was determined using Archimedes' principle. In the case of the volume measurements, 5 pieces of standard and 5 pieces of MF BFMs were tested. The whole volume of the standard and MF BFM of the CHS was $64.40 \pm 6.54 \text{ cm}^3$ and $73.20 \pm 4.97 \text{ cm}^3$, respectively. The data are tabulated in Table 3. The BFMs were not preheated before being inserted into the die tool.

Table 3. Results of the volume measurements

	Standard BFMs	MF BFMs
No. of samples	5	5
Weight (g)	68.72 ± 4.52	78.32 ± 4.23
Volume of CHSs (cm^3)	64.40 ± 6.54	73.20 ± 4.97
Volume fraction of CHSs (%)	40.17 ± 4.08	45.66 ± 3.10

The mass of the castings was measured using a scale, and the average weights of the pieces were compared at different pressure levels. The average masses and their standard deviations are listed in Table 4., in which the samples manufactured using maximum space filling (MF) have been marked. The mass changes (compared to the solid reference), the densities, and the relative densities are also shown in Table 4.

Table 4. Mass weighing results.

Sample	Pressure (MPa (bar))	Mass (g)	Mass change (%)	Density (gcm ⁻³)	Relative density (-)
Solid	24 (240)	416 ± 2.9	0	2.60 ± 0.02	1.00 ± 0.000
O	0 (0)	331 ± 3.9	20.5 ± 1.2	2.03 ± 0.01	0.78 ± 0.004
A	14 (140)	341 ± 23.7	18.0 ± 5.7	2.19 ± 0.24	0.84 ± 0.014
B	18 (180)	334 ± 20.2	19.7 ± 4.9	2.08 ± 0.16	0.80 ± 0.048
C (MF)	20 (200)	315 ± 12.9	24.3 ± 3.2	1.93 ± 0.03	0.74 ± 0.009
D	22 (220)	336 ± 15.4	19.3 ± 3.8	2.07 ± 0.11	0.79 ± 0.034
E (MF)	24 (240)	323 ± 3.5	22.4 ± 1.1	1.99 ± 0.01	0.77 ± 0.002
F	26 (260)	331 ± 10.1	20.4 ± 2.5	2.07 ± 0.02	0.80 ± 0.007
G	28 (280)	331 ± 9.6	20.6 ± 2.4	2.06 ± 0.03	0.79 ± 0.008

For better oversight and understanding, the mass, mass changes, and densities are plotted in Fig. 5.

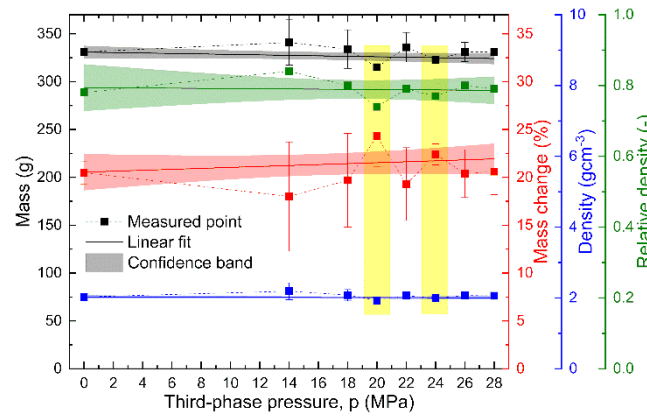


Figure 5. Mass, mass change, density, and relative density values of the investigated AMSFs.

The average mass of the cast samples ranged between 315 g and 341 g, with a grand average of 331 ± 3.9 g. The solid samples were measured to be 416 ± 2.9 g, which served as the basis for the mass change calculations. The MF-loaded castings (highlighted by a yellow background in Fig. 5.) showed the largest mass changes, namely $24.3 \pm 3.2\%$ and $22.4 \pm 1.1\%$ for the C and E samples, respectively. The lowest change was observed in sample A: $18.02 \pm 5.70\%$. The average change was $20.63 \pm 1.81\%$ across the whole sample set. In the case of the MF samples, the difference can be clearly explained by the space fillers being maximized for volume. The density values were calculated by dividing the measured mass by the volume of the samples, while the relative densities were derived as the ratio of the samples' density and the density of the matrix alloy (2.76 gcm^{-3}). Basic statistical analysis were performed on the measured values, including linear fitting and the calculation of the 95% confidence bands as plotted in Fig. 5., the equations are:

$$m = 330.8 - 0.24p \quad (\text{Eq. 2})$$

$$\Delta m = 20.5 + 0.05p \quad (\text{Eq. 3})$$

$$\rho = 2.03 - 0.007p \quad (\text{Eq. 4})$$

$$\rho_{\text{rel}} = 0.79 - 0.002p \quad (\text{Eq. 5})$$

Where m , Δm , ρ , ρ_{rel} , and p are the mass, the mass change, the density, the relative density (dependent variables), and the third phase pressure (independent variable) (Eq. 2-5), respectively. The equations show slight, almost negligible changes in the properties with respect to the applied third-phase pressure; the only outstanding cases are the aforementioned MF samples.

3.2. CT, macro- and microstructure

CT measurements were performed to investigate the macrostructure of the samples and to separate the gas and shrinkage porosity of the matrix, which are caused by the technological properties of HPDC and by the hollow filler. The analysis module separated the voids in the reconstructed CT results based on the sphericity. The calculated volumetric change is based on a comparison between the entire casting volume and the extracted volume, and it is listed in Table 5.

Table 5. Volumetric change based on CT results.

Sample	Pressure MPa (bar)	Volumetric change by CT (%)
Solid	24 (240)	-
O	0 (0)	32.7
A	14 (140)	37.5
B	18 (180)	32.8
C (MF)	20 (200)	50.9
D	22 (220)	24.2
E (MF)	24 (240)	41.3
F	26 (260)	43.0
G	28 (280)	37.7

The average volume gain across the entire sample series is 37.5%. For the C and E samples, the percentage change in space-filling due to the MF arrangement shows outstanding values, 50.9 and 41.3%, respectively. Although the value of the given sample F is more favorable than that of E, the reason for this is the infiltrated reinforcement particles shown in (Fig. 6f). At the same time, this phenomenon also adversely affects the strongly below-average volume loss of the sample D (Fig. 6e).

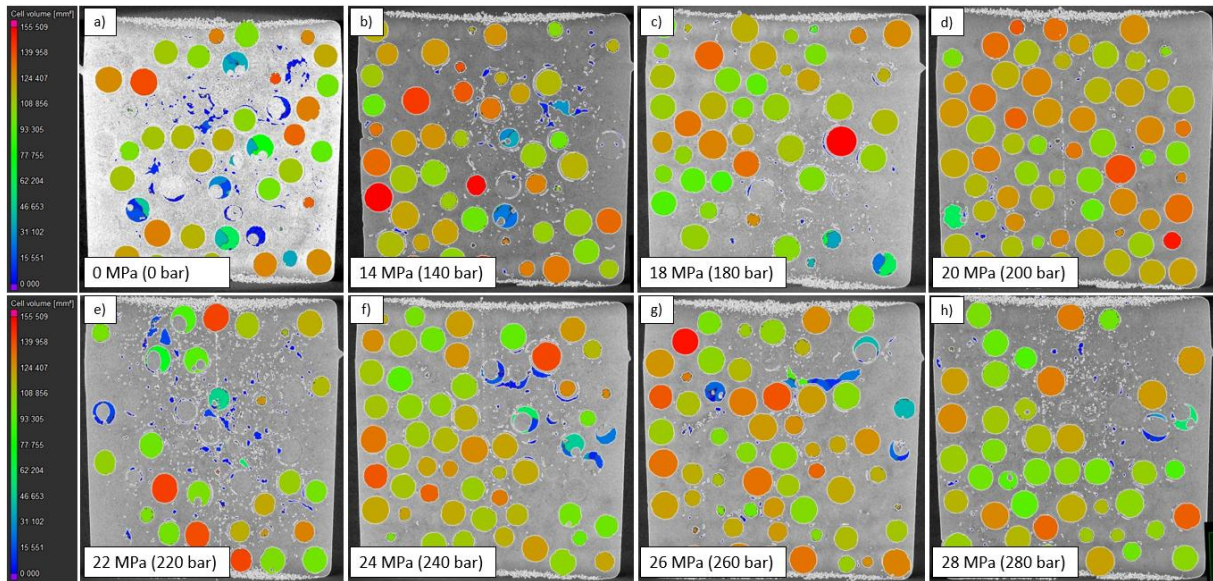


Figure 6. The reconstructed CT longitudinal sections of the die-cast AMSFs with the third phase applied pressures of: (a) 0 MPa (0 bar), (b) 14 MPa (140 bar), (c) 18 MPa (180 bar), (d) 20 MPa (200 bar), (e) 22 MPa (220 bar), (f) 24 MPa (240 bar), (g) 26 MPa (260 bar), and (h) 28 MPa (280 bar).

The microstructural LOM and SEM examination of the AMFS samples included the filling of gaps between space fillers, inspection of the CHS and matrix interfaces, identification of matrix inhomogeneities, and detection of broken filler material. The inhomogeneities exhibited in Figure 7 are generally minor gas porosities and minor shrinkage voids, which are a natural consequence of the HPDC process. However, given their quantity and size, their presence is negligible. The gaps between the fillers are completely filled, and the interface shows excellent contact (Fig. 7.). It can also be seen that the molten metal perfectly surrounds the CHS due to the pressure in the third phase (Fig. 8.).

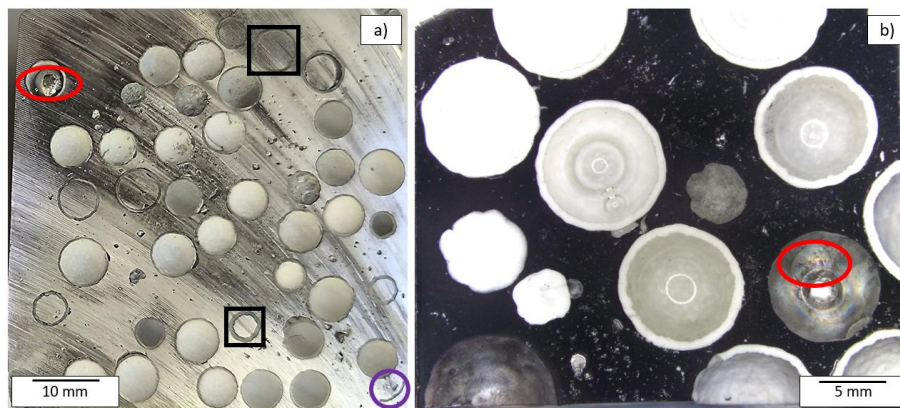


Figure 7. LOM images of sample E (240 bar) with typical defects.

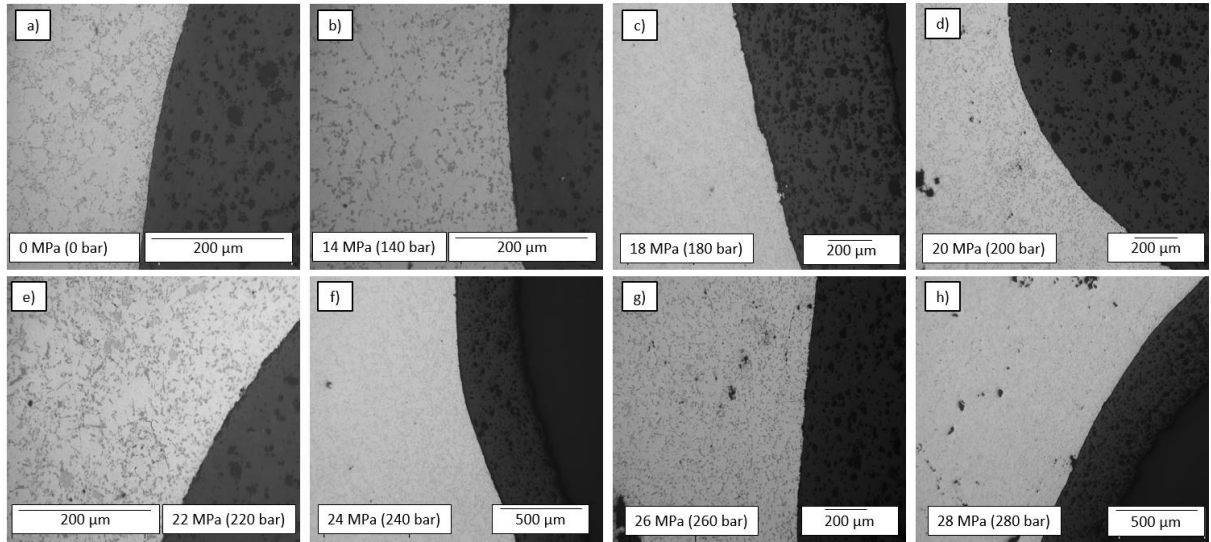


Figure 8. LOM images of the aluminum and CHS contact surfaces at each pressure level.

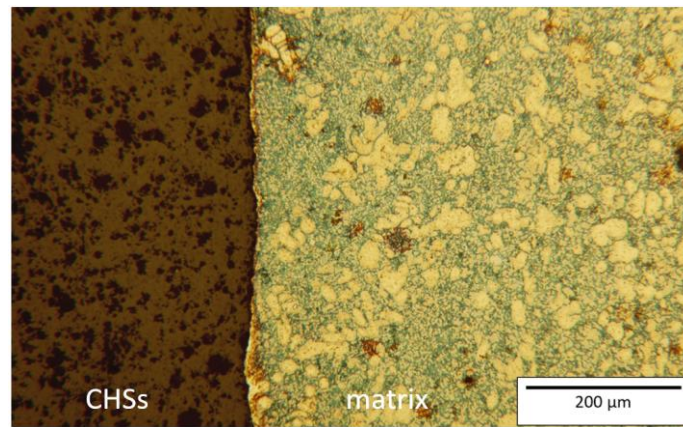


Figure 9. Color etched image of the interface between the hollow sphere shell and the matrix material (sample E (240 bar)).

The dendritic structure, typical of casting, is evident in the matrix morphology on the right side of Fig. 9. The etching resulted in different microstructural features appearing in different colors when observed under an optical microscope. In the micrograph, the greenish-blue network within the aluminum matrix corresponds to the Al–Si eutectic, while the lighter regions represent the primary α -Al phase. The ceramic–metal interface is continuous, and no optically resolvable thick reaction layer is visible, indicating proper load transfer between the two parts. This may be consistent with good infiltration and a suppressed chemical reaction between the constituents [52].

However, it is also apparent that the increase in the pressure value of the third phase flows into the hollow cavity through the cracks of the fillers and either fills them (Fig. 7a, marked with black square) or causes the particles to break (Fig. 7a, marked with purple circle) and finally fail. Nevertheless, the thin-walled CHS usually resisted the pressure of the third phase. In some extraordinary cases of the inspected cross-sections by LOM, solidified aluminum metal droplets were visible on the inner surface of the CHS (Fig. 7a and 7b, marked with red ellipse). With increasing pressure, the droplets increased in size or, in some cases, completely filled the CHS. Broken CHSs are visible at all pressure levels; their number is small (less than 5 % at the cross-sections) and typically does not differ, due to the natural surface cracks in the CHS. The distribution of the filled or collapsed reinforcements within the samples is typically localized to the interior of the piece or near the venting side.

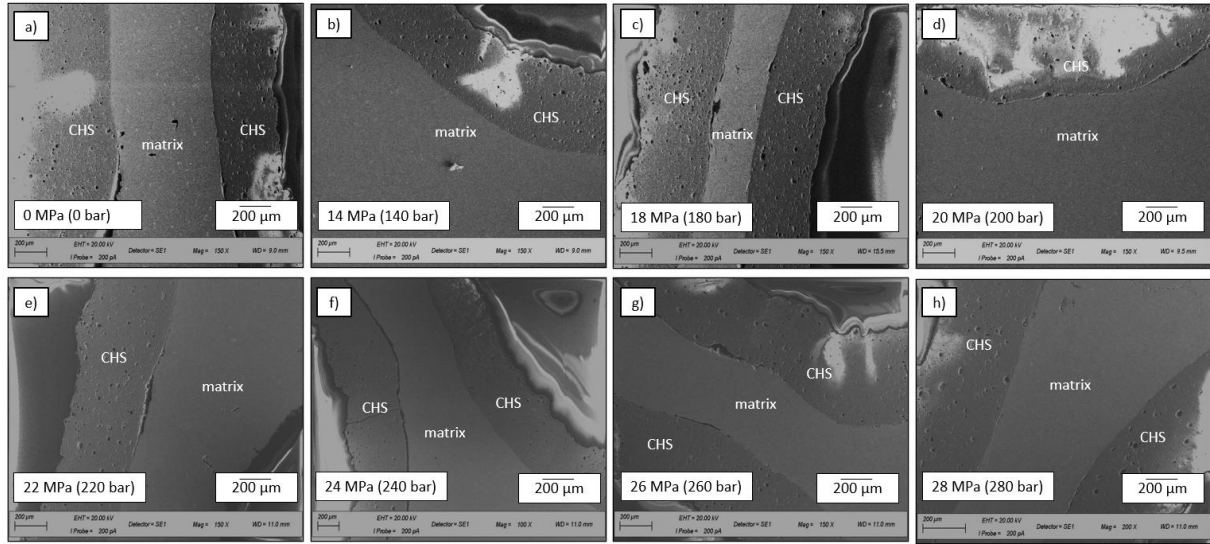


Figure 10. SEM images of the produced foam samples.

The interface regions between the CHSs and the matrix have been investigated by SEM. Typical CHS and matrix contact interfaces are shown in SEM images (Fig. 10). The interfaces are almost perfect, but not completely flawless; small shrinkage pores (~5% of the total interface surface) are visible, yet good contact with the filler remains. Fig. 11. represents a line EDS measurement of the interface region between the matrix material and a single CHS. The matrix and CHS interface is marked with a dashed blue line. The line EDS measurement is indicated by the orange line.

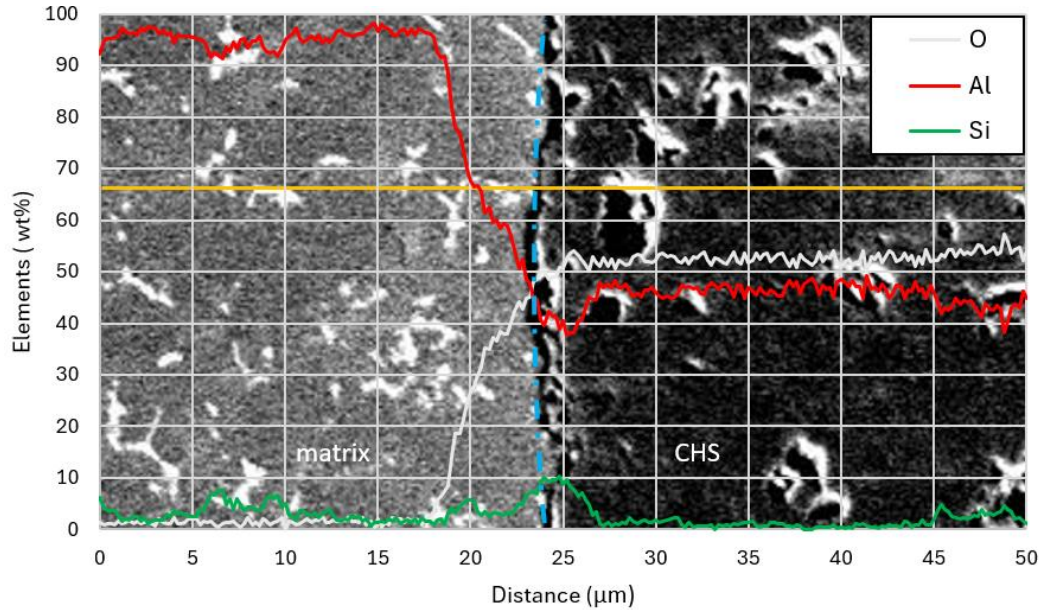


Figure 11. Line EDS measurement result on sample F (26 MPa (260 bar))

Both LOM and SEM examinations of the die-cast samples confirmed the feasibility of HPDC as the manufacturing process. CT and LOM examinations confirmed that the CHS bonds were broken by the aluminum melt flow, and the CHSs were separated from each other; therefore, their location changed randomly during solidification. Therefore, in the case of MF bonds, since the space filling of the spheres was high, the reinforcements remained much closer to each other, and their order was preserved. Therefore, samples C and E exhibited the lowest $W_{0.5}$ and SEA values because the aluminum matrix was not able to withstand such a large deformation.

3.3. Characteristic compressive properties

The AMSF with CHS filler can be described as an advanced reinforced composite with distinct physical advantages. The metallic properties of the matrix play an important role in the characteristic mechanical properties of AMSFs, while the hollow, closed-surface CHS filler also plays a key role in the load-bearing capacity and deformation process. In this study, uniaxial compression test was used to determine the characteristic mechanical responses, in accordance with ISO 13314:2011 [46], as a standard basis for evaluation. All data in Table 6. are based on the results of 3 cast specimens for each parameter set.

Table 6. The characteristic mechanical properties of the investigated AMSFs.

Sample type	Pressure (MPa) ((bar))	σ_c (MPa)	ϵ_c (-)	σ_{pl} (MPa)	$W_{0.5}$ (Jcm ⁻³)	SEA (Jg ⁻¹)
O	0 (0)	137.2 ± 4.7	0.054 ± 0.003	92.7 ± 19.0	47.0 ± 5.7	23.8 ± 2.7
A	14 (140)	140.0 ± 10.2	0.061 ± 0.012	87.7 ± 5.8	52.9 ± 3.3	26.4 ± 1.1
B	18 (180)	148.2 ± 11.6	0.057 ± 0.012	110.7 ± 19.0	55.1 ± 8.2	27.0 ± 2.7
C (MF)	20 (200)	141.6 ± 4.3	0.049 ± 0.001	96.6 ± 6.6	43.2 ± 3.8	23.0 ± 1.8
D	22 (220)	155.5 ± 14.4	0.057 ± 0.005	102.7 ± 20.6	53.8 ± 7.6	26.6 ± 2.5
E (MF)	24 (240)	147.7 ± 1.6	0.051 ± 0.001	94.4 ± 7.2	48.6 ± 1.8	25.0 ± 1.0
F	26 (260)	161.1 ± 5.4	0.054 ± 0.001	103.2 ± 17.6	52.0 ± 8.3	25.8 ± 4.1
G	28 (280)	153.4 ± 6.5	0.054 ± 0.002	104.9 ± 6.4	55.9 ± 1.0	27.9 ± 0.4
Average		151.1 ± 10.4	0.055 ± 0.005	99.1 ± 12.8	51.1 ± 5.0	25.7 ± 2.0

Fig. 12. shows the uniaxial compressive engineering stress-engineering strain curves and the absorbed mechanical energy-engineering strain curves, respectively.

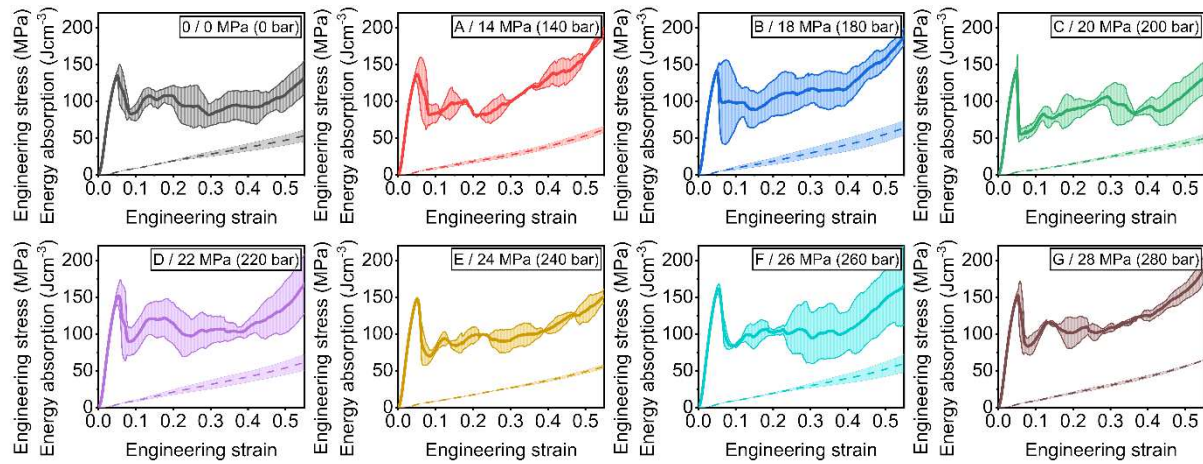


Figure 12. The compressive engineering stress-engineering strain (continuous lines with standard deviation bands) and energy absorption-engineering strain (dashed lines with standard deviation bands) curves of the die-cast AMSFs.

The curves follow the typical behavior of MMSFs [57,58]. The engineering stress-engineering strain diagrams start with a quasi-linear part that corresponds to an almost elastic deformation. In reality, the plastic deformation of the thin matrix walls between the CHSs and the small spatial movement of the rigid CHSs start earlier in this phase, as it was shown by acoustic emission and modal analysis measurements [59]. The quasi-linear part culminates in a local stress peak, referred to as the compressive strength (σ_c). Compressive strength is one of the most important characteristics of AMSFs,

representing their load-bearing capacity. The corresponding engineering strain value is the fracture strain (ϵ_c) at which the first cleavage plane appears in the samples (see Fig. 14). The introduction of the cleavage plane results in a definite stress drop (~30-50%) in the diagrams. The last and longest part of the curves, connected to the deformation and failure of the samples, typical of MMSFs, is referred to as the plateau region. The investigated AMSFs showed increasing plateau regions. The plateau region can be characterized by the plateau stress (σ_{pl}). Regarding the energy absorption properties of MMSFs, the absorption can be described in the function of the engineering strain as plotted in Fig. 12. However, the most important characteristics are the absorbed energy at a specific (usually 0.5) engineering strain ($W_{0.5}$, measured in Jcm^{-3}) and its specific version, the specific energy absorption (SEA, $W_{0.5}$ divided by the density).

Fig. 13 represents the compressive strength, the plateau strength (solid markers), and their corresponding specific values (hollow markers) as a function of the third-phase pressure.

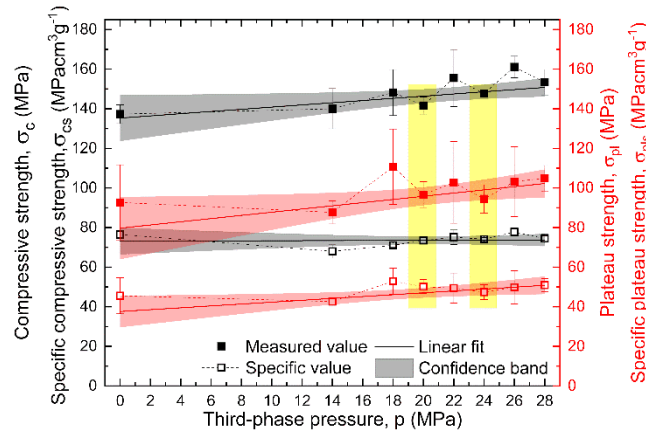


Figure 13. The compressive and the plateau strength of the investigated AMSFs and their specific values as a function of the third-phase pressure.

Sample 0 exhibited the lowest strength values. Both the compressive and plateau strengths increased with third-phase pressure. These tendencies can be described by simple linear equations (Eq. 6-7):

$$\sigma_c = 135.3 + 0.55p \quad (\text{Eq. 6})$$

$$\sigma_{pl} = 79.7 + 0.81p \quad (\text{Eq. 7})$$

Regarding the specific values, the density-specific compressive strength was almost insensitive to the third-phase pressure during production, represented by the almost-zero coefficient of the pressure in Eq. 8.

$$\sigma_{cs} = 73.1 + 0.02p \quad (\text{Eq. 8})$$

The specific plateau strength followed the trend of the absolute plateau strength, but with a significantly more moderate slope (Eq. 9).

$$\sigma_{pls} = 37.6 + 0.47p \quad (\text{Eq. 9})$$

Along with the fitted line, the 95% confidence bands were plotted to highlight the uncertainties of the fittings originating from the relatively high standard deviations of the individual points. On the other hand, MMSFs always have higher standard deviations in their compressive strength values (i) due to their stochastic macrostructure and (ii) especially in the case of rigid matrix materials. The MF samples (highlighted in yellow) fell close to the fitted lines, and their standard deviations were small,

indicating highly repeatable properties; however, they exhibited no outstanding compressive properties.

The fracture strain (ϵ_c) results are plotted in Fig. 14. The fracture strains ranged between 0.048 and 0.061, and they do not show any reasonable correlation with the third-phase pressure.

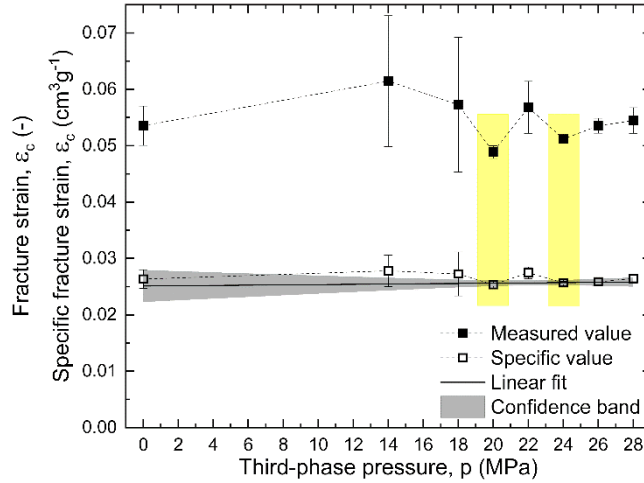


Figure 14. The fracture strains of the investigated AMSFs and their specific values as a function of the third-phase pressure.

Contrarily, the specific values scattered around $0.025 \text{ cm}^3\text{g}^{-1}$ and their trend can be described by a linear relationship (Eq. 10).

$$\epsilon_c = 0.0251 + 0.00002p \quad (\text{Eq. 10})$$

The MF samples exhibited lower fracture strains, due to the close-packed arrangement of the rigid CHSs. The energy absorption properties are plotted in Fig. 15.

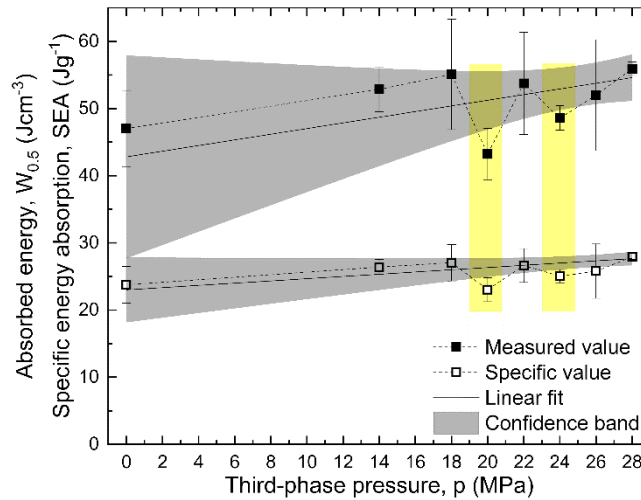


Figure 15. The energy absorption properties of the investigated AMSFs as a function of the third-phase pressure.

The energy absorption is smooth, without any significant knee-points in the energy absorption-engineering strain curves (Fig. 12). The average $W_{0.5}$ value is $51.1 \pm 5.0 \text{ Jcm}^{-3}$ compared to the MF samples exhibiting the lowest results in terms of absorbed energy ($43.2 \pm 3.8 \text{ Jcm}^{-3}$ (sample C) and $48.6 \pm 1.8 \text{ Jcm}^{-3}$ (sample E)), corresponding to a decrease of 7.9 Jcm^{-3} and 2.5 Jcm^{-3} , respectively. The main reason for the difference is that the higher CHS content results in less matrix filling the internal

spaces, so the deformable load-bearing cross-section is smaller. The energy absorption can only be described by a wide confidence band (Eq. 11), as shown in Fig. 15.

$$W_{50} = 42.8 + 0.42p \quad (\text{Eq. 11})$$

Similar trends can be observed for the SEA, but the confidence band of the fit is significantly narrower, indicating higher reliability of the fitted line (Eq. 12).

$$\text{SEA} = 23.0 + 0.17p \quad (\text{Eq. 12})$$

The third-phase pressure is important from a production standpoint; however, it makes it harder to compare the characteristic properties with the literature data. For porous materials, the relative density is a widely accepted base for comparison. Therefore, the characteristic properties are also analyzed with respect to the relative density of the samples, as plotted in Fig. 16, for the strength values.

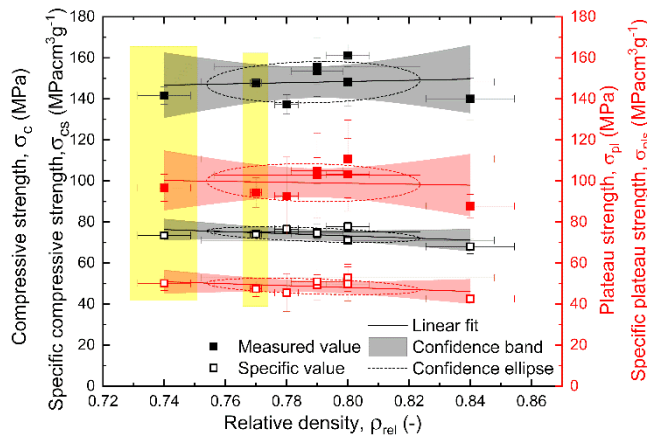


Figure 16. The compressive and the plateau strength of the investigated AMSFs and their specific values as a function of the relative density.

In Fig. 16, slight changes can be observed in the 0.1 wide relative density range (from 0.74 to 0.84). The measured compressive strength (Eq. 13) increased with relative density, but the standard deviations indicate relatively high uncertainty at the 95% confidence level.

$$\sigma_c = 125.1 + 29.19\rho_{\text{rel}} \quad (\text{Eq. 13})$$

The plateau strength (Eq. 14) exhibited a similar trend and a similar confidence band, but with a moderate negative slope.

$$\sigma_{\text{pl}} = 117.3 - 23.12\rho_{\text{rel}} \quad (\text{Eq. 14})$$

The plotted 95% confidence ellipses predict narrower relative density ranges (from ~0.75 to ~0.82) for future production, with slightly higher standard deviations (as the ellipses are typically wider in this region).

The specific compressive strength (Eq. 15) and the specific plateau strength (Eq. 16) negative slope lines could be fitted. Their slopes are approximately twice those of the absolute measured properties, and they are negative in both cases. Their confidence bands and ellipses are also narrower, representing lower uncertainties in the specific properties.

$$\sigma_{\text{cs}} = 114.4 - 51.50\rho_{\text{rel}} \quad (\text{Eq. 15})$$

$$\sigma_{\text{pls}} = 85.7 - 47.03\rho_{\text{rel}} \quad (\text{Eq. 16})$$

The lowest relative density values belong to the most packed filler MF samples (0.74 ± 0.009 for sample C (20 MPa (200 bar) and 0.77 ± 0.002 for sample E (24 MPa (240 bar))), respectively). Accordingly, these samples provided the highest specific strength values, namely 73.5 ± 1.35 MPa (σ_{cs}) and 96.6 ± 6.57 MPa (σ_{pls}) for sample C (20 MPa (200 bar)), while 74.1 ± 0.83 MPa (σ_{cs}) and 47.4 ± 3.75 MPa (σ_{pls}) for sample E (24 MPa (240 bar)).

The same analyses were performed for the energy absorption properties, the results are plotted in Fig. 17.

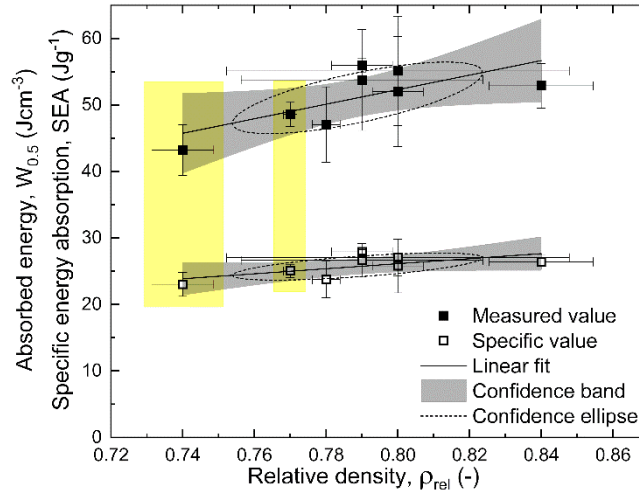


Figure 17. The energy absorption properties of the investigated AMSFs as a function of the relative density.

The absorbed mechanical energy demonstrates moderate changes across the investigated range of relative density (Eq. 17), while the specific energy absorption changed slightly (Eq. 18). Both properties demonstrate a positive correlation with relative density; increasing relative density resulted in higher absorbed energy values. The MF samples were able to accommodate the lowest absorbed energies due to their closely packed structure and more hectic plateau (Fig. 12.). Increasing third-phase pressure produced only a limited increase in strength because the load-bearing mechanism is mainly governed by the ceramic hollow spheres rather than by minor densification of the matrix.

$$W_{50} = -35.1 + 109.29\rho_{rel} \quad (\text{Eq. 17})$$

$$SEA = -4.1 + 37.84\rho_{rel} \quad (\text{Eq. 18})$$

AMSFs were originally developed for lightweight structural and energy-absorbing applications, but later their energy-absorption capacity came into focus due to the typically high standard deviation of compressive strength (which serves as the design limit load-bearing capacity). Therefore, the SEA values are shown separately in Fig. 18, along with those for similar AMSF structures found in the literature. The purple triangles illustrate the values obtained in the present study (Fig. 18.).

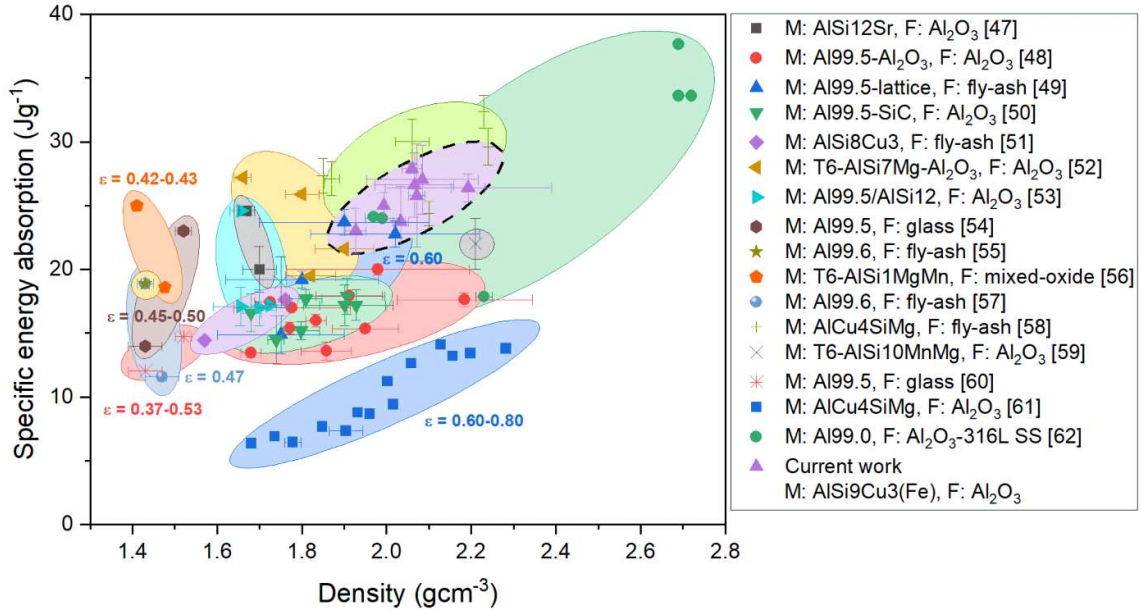


Figure 18. SEA of various CHS-filled AMSFs (M: matrix material(s), F: applied filler material(s)). The upper limit strain corresponds to 0.5, unless otherwise stated [43,44,60–73].

3.4. Failure modes

The three images in Fig. 19 show the typical progressive compressive failure of a HPDC AMSFs (sample D 22 MPa (220 bar)), for the remaining samples see in the *Supporting materials*. The initial stage is typically ductile yielding, when the load distribution is uniform. There are no visible macrocracks yet, and slight barreling of the cylinder can be observed. In the second stage, usually one, dominating crack propagates diagonally across the specimen. Under compression, the failure mode was shear, and the shear stress plane was $\sim 45^\circ$. The crack is relatively sharp and localized, the initiation defects (porosity) or the lack of material continuity of the cylinder shell in the vicinity of a CHS. In the final stage, when structural integrity is completely lost, the material breaks into multiple fragments. There is no significant plastic deformation throughout the process. The crack propagation is brittle-dominated final failure, and low energy absorption after crack propagation.

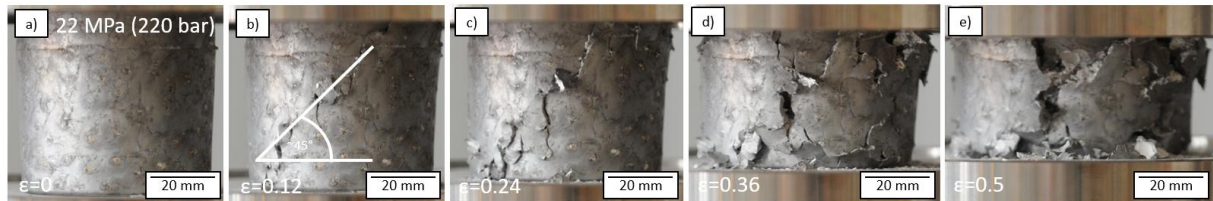


Figure 19. The monitored deformation of sample D (22 MPa (220 bar)) during the measurement: (a) quasi-elastic part $\epsilon=0$, (b) just after the first crack $\epsilon=0.12$, (c) when the crack spreads $\epsilon=0.24$, (d) just after σ_c , cell and matrix collapse $\epsilon=0.36$, and (e) at 0.5 engineering strain (end of test).

In summary, the specimen exhibits shear-dominated compressive failure with defect-controlled crack initiation and brittle final fragmentation. This crack propagation was typical of all CHS-filled HPDC AMSFs.

4. Conclusions

In this study, AlSi9Cu(Fe) matrix AMSFs were produced with high CHS filler volume fraction by HPDC. From the observations and investigations detailed above, the following conclusions can be drawn.

- Horizontal high-pressure cold-chamber die-casting (HPDC) is a feasible and efficient process for the large-scale mass production of bonded CHS-filled AMSFs. The combination of waterglass coating of CHSs and heat treatment to ensure solidification is a feasible method for placing and situating the fillers in a fixed shape into the die as a bonded filler material (BFM).
- The HPDC manufacturing process has been demonstrated to provide compressive properties that exhibit high levels of repeatability (sample C and E), thus indicating its suitability for industrial production settings where low property scatter (σ_c of 141.6 ± 4.3 MPa and 147.7 ± 1.6 MPa, respectively) is an essential criterion.
- The results of the uniaxial compression tests demonstrate that the failure of the AMSFs occurs after a peak value (compressive strength) that is a characteristic property and design limit of AMSFs. The AMSFs with the highest filler content have lower specific energy absorption (SEA) than under the standard filling condition.
- Maximizing the CHS content does not maximize energy absorption, an optimum filler fraction exists where weight reduction and mechanical performance are balanced.
- During the process of the uniaxial compression tests, the CHSs collaborated with the metal matrix. However, the waterglass bonds that endow the spherical shells with their shape are susceptible to separation during the filling phase, a consequence of the intense metal flow.
- The continuous CHS-matrix interface facilitates efficient load transfer ($\sigma_c = 140\text{--}160$ MPa), ensuring the active participation of the ceramic shells in load bearing during compression.

Given the specified geometry, the third-phase of HPDC at 20 MPa (200 bar) for sample C is shown to yield the optimal space-filling result. At this pressure, the gap between the CHSs is completely filled with matrix metal, while the shells have not yet begun to fill or collapse from a casting perspective. Furthermore, the SEA values of samples B (18 MPa (180 bar)) and G (28 MPa (280 bar)) were excellent from a mechanical point of view. The casting optimum (20 MPa (200 bar)) and the mechanical optimum (26–28 MPa (260–280 bar)) are shown to be non-overlapping, indicating a trade-off between preserving hollow sphere integrity and maximizing load-bearing performance.

Author Contributions

All authors contributed to the study conception and design. The first draft of the manuscript was written by Péter SZALVA and all authors commented on previous versions of the manuscript. Conceptualization: Péter SZALVA, Imre Norbert ORBULOV; Methodology: Péter SZALVA, Alexandra KEMÉNY; Material preparation: Péter SZALVA, Ibolya KARDOS, Dóra KÁROLY, Anna SZIJÁRTÓ, Tamás BUBONYI, Melissza ZSOLDOS, Alexandra KEMÉNY; Formal analysis and investigation: Péter SZALVA, Alexandra KEMÉNY; Writing - original draft preparation: Péter SZALVA; Writing - review and editing: Alexandra KEMÉNY; Resources: Tamás RICK; Supervision: Imre Norbert ORBULOV; All authors read and approved the final manuscript.

Competing interest

The author declare that they have no competing interests.

Data availability

The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Funding

The authors received no specific funding.

References

- [1] S. Broxtermann, M.M. Su, H. Hao, T. Fiedler, Comparative study of stir casting and infiltration casting of expanded glass-aluminium syntactic foams, *J. Alloys Compd.* 845 (2020) 155415. <https://doi.org/10.1016/j.jallcom.2020.155415>.
- [2] K. Al-Sahlani, S. Broxtermann, D. Lell, T. Fiedler, Effects of particle size on the microstructure and mechanical properties of expanded glass-metal syntactic foams, *Materials Science and Engineering A* 728 (2018) 80–87. <https://doi.org/10.1016/j.msea.2018.04.103>.
- [3] M. Su, H. Wang, H. Hao, T. Fiedler, Compressive properties of expanded glass and alumina hollow spheres hybrid reinforced aluminum matrix syntactic foams, *J. Alloys Compd.* 821 (2020) 153233. <https://doi.org/10.1016/j.jallcom.2019.153233>.
- [4] N. Movahedi, E. Linul, Mechanical properties of Light Expanded Clay Aggregated (LECA) filled tubes, *Mater. Lett.* 217 (2018) 194–197. <https://doi.org/10.1016/j.matlet.2018.01.078>.
- [5] A.M. Rashad, Lightweight expanded clay aggregate as a building material – An overview, *Constr. Build. Mater.* 170 (2018) 757–775. <https://doi.org/10.1016/j.conbuildmat.2018.03.009>.
- [6] H. Puga, V.H. Carneiro, C. Jesus, J. Pereira, V. Lopes, Influence of particle diameter in mechanical performance of Al expanded clay syntactic foams, *Compos. Struct.* 184 (2018) 698–703. <https://doi.org/10.1016/j.compstruct.2017.10.040>.
- [7] S. Bazzaz Bonabi, J. Kahani Khabushan, R. Kahani, A. Honarbakhsh Raouf, Fabrication of metallic composite foam using ceramic porous spheres “Light Expanded Clay Aggregate” via casting process, *Mater. Des.* 64 (2014) 310–315. <https://doi.org/10.1016/j.matdes.2014.07.061>.
- [8] M. Taherishargh, I.V. Belova, G.E. Murch, T. Fiedler, Pumice/aluminium syntactic foam, *Materials Science and Engineering: A* 635 (2015) 102–108. <https://doi.org/10.1016/j.msea.2015.03.061>.
- [9] M.K. Mirzarahimi, H. Khodarahmi, M. Ziashamami, R. Hosseini, Numerical and Experimental Study of the Use of Mineral Pumice in the Core of the Sandwich Panel to Absorb the Shock Wave, *Periodica Polytechnica Mechanical Engineering* 67 (2023) 19–29. <https://doi.org/10.3311/PPme.19341>.
- [10] Ç. Bolat, İ.C. Akgün, A. Gökşenli, Effects of particle size, bimodality and heat treatment on mechanical properties of pumice reinforced aluminum syntactic foams produced by cold chamber die casting, *China Foundry* 18 (2021) 529–540. <https://doi.org/10.1007/s41230-021-1133-4>.

- [11] M. Borovinšek, M. Taherishargh, M. Vesenjaj, Z. Ren, T. Fiedler, Geometrical characterization of perlite-metal syntactic foam, *Mater. Charact.* 119 (2016) 209–215. <https://doi.org/10.1016/j.matchar.2016.07.024>.
- [12] M. Taherishargh, E. Linul, S. Broxtermann, T. Fiedler, The mechanical properties of expanded perlite-aluminium syntactic foam at elevated temperatures, *J. Alloys Compd.* 737 (2018) 590–596. <https://doi.org/10.1016/J.JALLCOM.2017.12.083>.
- [13] M. Taherishargh, I. V Belova, G.E. Murch, T. Fiedler, On the mechanical properties of heat-treated expanded perlite–aluminium syntactic foam, *Mater. Des.* 63 (2014) 375–383. <https://doi.org/10.1016/j.matdes.2014.06.019>.
- [14] Ç. Bolat, İ.C. Akgün, A. Gökşenli, Effect of Aging Heat Treatment on Compressive Characteristics of Bimodal Aluminum Syntactic Foams Produced by Cold Chamber Die Casting, *International Journal of Metalcasting* 16 (2022) 646–662. <https://doi.org/10.1007/s40962-021-00629-0>.
- [15] X.F. Tao, L.P. Zhang, Y.Y. Zhao, Al matrix syntactic foam fabricated with bimodal ceramic microspheres, *Mater. Des.* 30 (2009) 2732–2736. <https://doi.org/10.1016/j.matdes.2008.11.005>.
- [16] P. Kubelka, C. Kádár, N. Jost, Effect of the interface on the compressive properties of magnesium syntactic foams, *Mater. Lett.* 287 (2021) 129293. <https://doi.org/10.1016/j.matlet.2020.129293>.
- [17] C. Kádár, P. Kubelka, A. Szlancsik, On the compressive properties of aluminum and magnesium syntactic foams: Experiment and simulation, *Mater. Today Commun.* 35 (2023) 106060. <https://doi.org/10.1016/j.mtcomm.2023.106060>.
- [18] G. Anbuechezhiyan, B. Mohan, D. Sathianarayanan, T. Muthuramalingam, Synthesis and characterization of hollow glass microspheres reinforced magnesium alloy matrix syntactic foam, *J. Alloys Compd.* 719 (2017) 125–132. <https://doi.org/10.1016/j.jallcom.2017.05.153>.
- [19] E. Linul, D. Lell, N. Movahedi, C. Codrean, T. Fiedler, Compressive properties of zinc syntactic foams at elevated temperatures, *Compos. B Eng.* 167 (2019) 122–134. <https://doi.org/10.1016/j.compositesb.2018.12.019>.
- [20] N. Movahedi, G. Murch, I. Belova, T. Fiedler, Effect of Heat Treatment on the Compressive Behavior of Zinc Alloy ZA27 Syntactic Foam, *Materials* 12 (2019) 792. <https://doi.org/10.3390/ma12050792>.
- [21] L. Peroni, M. Scapin, C. Fichera, D. Lehmkus, J. Weise, J. Baumeister, M. Avalu, Investigation of the mechanical behaviour of AISI 316L stainless steel syntactic foams at different strain-rates, *Compos. B Eng.* 66 (2014) 430–442. <https://doi.org/10.1016/j.compositesb.2014.06.001>.
- [22] G. Castro, S.R. Nutt, Synthesis of syntactic steel foam using mechanical pressure infiltration, *Materials Science and Engineering: A* 535 (2012) 274–280. <https://doi.org/10.1016/j.msea.2011.12.084>.
- [23] A. Rabiei, K. Karimpour, D. Basu, M. Janssens, Steel-steel composite metal foam in simulated pool fire testing, *International Journal of Thermal Sciences* 153 (2020) 106336. <https://doi.org/10.1016/j.ijthermalsci.2020.106336>.

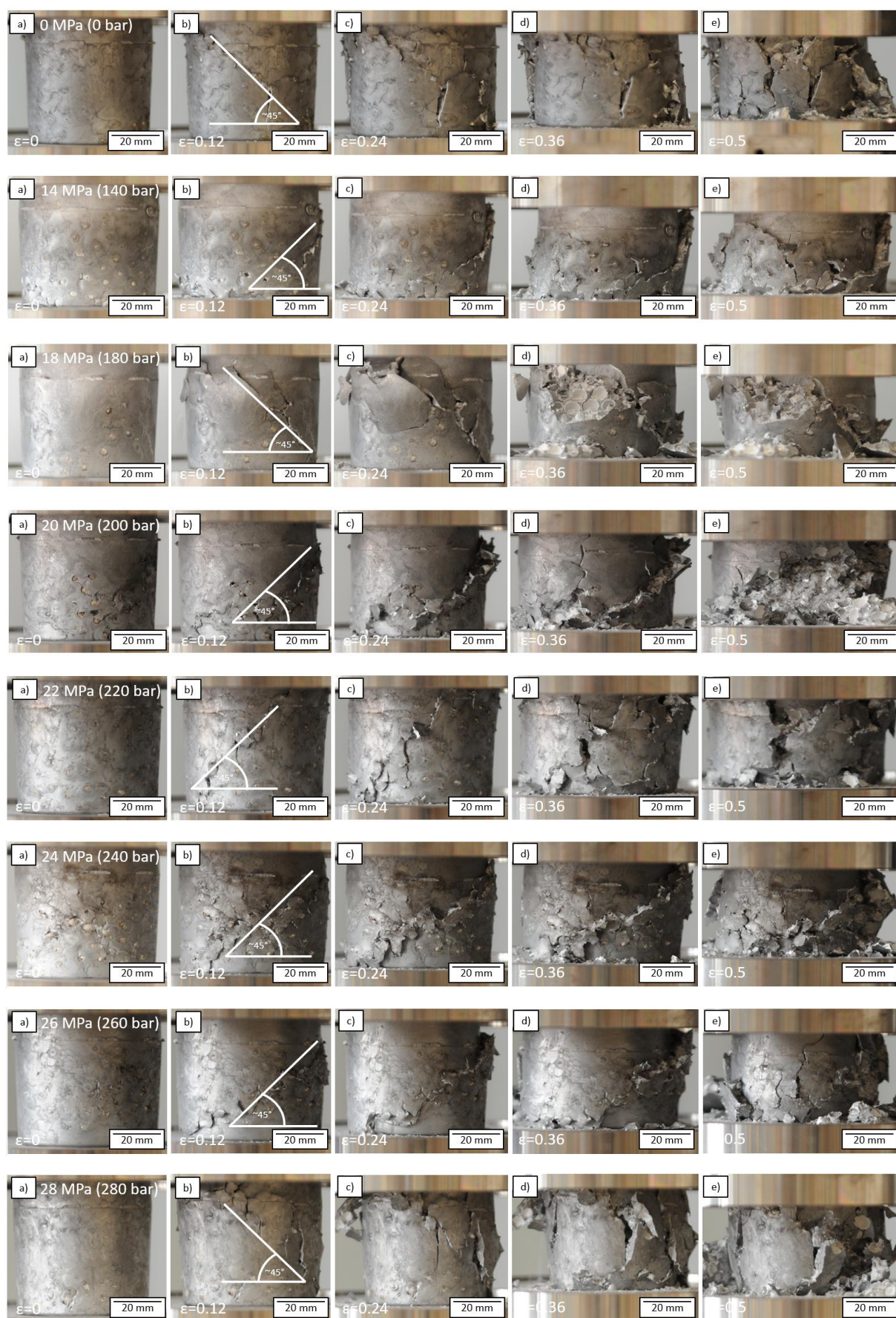
- [24] Q. Yang, B. Yu, H. Hu, G. Hu, Z. Miao, Y. Wei, W. Sun, Melt flow and solidification during infiltration in making steel matrix syntactic foams, *Materials Science and Technology (United Kingdom)* 35 (2019) 1831–1839. <https://doi.org/10.1080/02670836.2019.1650444>.
- [25] A.M. Sánchez de la Muela, J. Duarte, J. Santos Baptista, L.E. García Cambrónero, J.M. Ruiz-Román, F.J. Elorza, Stir Casting Routes for Processing Metal Matrix Syntactic Foams: A Scoping Review, *Processes* 10 (2022). <https://doi.org/10.3390/pr10030478>.
- [26] M. Su, H. Wang, H. Hao, Compressive Properties of Aluminum Matrix Syntactic Foams Prepared by Stir Casting Method, *Adv. Eng. Mater.* 21 (2019). <https://doi.org/10.1002/adem.201900183>.
- [27] I.N. Orbulov, Metal matrix syntactic foams produced by pressure infiltration-The effect of infiltration parameters, *Materials Science and Engineering A* 583 (2013) 11–19. <https://doi.org/10.1016/j.msea.2013.06.066>.
- [28] A.M. S-de-la-Muela, L.E.G. Cambrónero, J.M. Ruiz-Román, Molten Metal Infiltration Methods to Process Metal Matrix Syntactic Foams, *Metals (Basel)*. 10 (2020) 149. <https://doi.org/10.3390/met10010149>.
- [29] J.C. Carranza, B.Y. Casas, I.A. Figueroa, L.E. Carranza, I. Alfonso, Design, fabrication and operation of a device for manufacturing metal foams and composites by infiltration, *International Journal of Metalcasting* 17 (2023) 3019–3031. <https://doi.org/10.1007/s40962-023-00979-x>.
- [30] A. Kemény, B. Leveles, D.B. Kincses, D. Károly, Manufacturing and Investigation of In Situ and Ex Situ Produced Aluminum Matrix Foam-Filled Tubes, *Adv. Eng. Mater.* 24 (2022) 2100365. <https://doi.org/10.1002/adem.202100365>.
- [31] M. Taherishargh, M. Vesenjak, I.V. Belova, L. Krstulović-Opara, G.E. Murch, T. Fiedler, In situ manufacturing and mechanical properties of syntactic foam filled tubes, *Mater. Des.* 99 (2016) 356–368. <https://doi.org/10.1016/j.matdes.2016.03.077>.
- [32] I. Duarte, M. Vesenjak, L. Krstulović-Opara, I. Anžel, J.M.F. Ferreira, Manufacturing and bending behaviour of in situ foam-filled aluminium alloy tubes, *Mater. Des.* 66 (2015) 532–544. <https://doi.org/10.1016/j.matdes.2014.04.082>.
- [33] I. Duarte, L. Krstulović-Opara, M. Vesenjak, Axial crush behaviour of the aluminium alloy in-situ foam filled tubes with very low wall thickness, *Compos. Struct.* 192 (2018) 184–192. <https://doi.org/10.1016/j.compstruct.2018.02.094>.
- [34] V. Chilla, D.P. Mondal, G.D.J. Ram, M. Mukherjee, Processing of in-situ aluminium foam-filled stainless steel tube with foam-tube bonding for enhanced crashworthiness, *J. Manuf. Process.* 82 (2022) 488–500. <https://doi.org/10.1016/j.jmapro.2022.08.020>.
- [35] D. Dittrich, D. Lehmhus, M. Haesche, L. Fernandes Gomes, C. Pille, A. Jahn, L. Ullmann, C. Graner, Influence of secondary aluminum content on casting and weldability of high pressure die cast materials for sustainable automotive body concepts, *Journal of Advanced Joining Processes* 13 (2026) 100361. <https://doi.org/10.1016/J.JAJP.2025.100361>.
- [36] A.L. Strauch, M.R. Barbieri, A. Geppert, L. Achelis, U. Fritsching, D. Lehmhus, B. Schneider, A. Struss, A. Toenjes, Managing distortion in high pressure die casting: Evaluating a digital twin

- approach for real-time adjustment of quenching parameters, *Procedia Comput. Sci.* 276 (2026) 246–257. <https://doi.org/10.1016/J.PROCS.2026.02.030>.
- [37] V. Nyeste, T. Mikó, Á. Kazup, M. Mende-Tokárová, D. Molnár, V. Mertinger, A new approach to enhance the efficiency of local squeezing during high pressure die casting of aluminum alloys, *Mater. Des.* 266 (2026) 116131. <https://doi.org/10.1016/J.MATDES.2026.116131>.
 - [38] M. Merchán, A. Pascual, A. Jiménez, J.C. García, E. Anglada, H. Galarraga, N. Ortega, High-Pressure Die Casting (HPDC) Process Parameters Optimization for Al-Mg-Fe Aluminum Alloy Structural Parts Manufacturing, *Metals (Basel)*. 15 (2025). <https://doi.org/10.3390/met15101071>.
 - [39] E. Lordan, Y. Zhang, K. Dou, A. Jacot, C. Tzileroglou, S. Wang, Y. Wang, J. Patel, J. Lazaro-Nebreda, X. Zhou, T. Hashimoto, Z. Fan, High-Pressure Die Casting: A Review of Progress from the EPSRC Future LiME Hub, *Metals (Basel)*. 12 (2022). <https://doi.org/10.3390/met12101575>.
 - [40] P. Burggräf, G. Bergweiler, S. Kehrer, T. Krawczyk, F. Fiedler, Mega-casting in the automotive production system: Expert interview-based impact analysis of large-format aluminium high-pressure die-casting (HPDC) on the vehicle production, *J. Manuf. Process.* 124 (2024) 918–935. <https://doi.org/10.1016/J.JMAPRO.2024.06.028>.
 - [41] G.K. Sigworth, R.J. Donahue, The Metallurgy of Aluminum Alloys for Structural High-Pressure Die Castings, *International Journal of Metalcasting* 15 (2021) 1031–1046. <https://doi.org/10.1007/s40962-020-00535-x>.
 - [42] Z.X. Liang, B. Ye, L. Zhang, Q.G. Wang, W.Y. Yang, Q.D. Wang, A new high-strength and corrosion-resistant Al–Si based casting alloy, *Mater. Lett.* 97 (2013) 104–107. <https://doi.org/10.1016/J.MATLET.2013.01.112>.
 - [43] M.D. Goel, D.P. Mondal, M.S. Yadav, S.K. Gupta, Effect of strain rate and relative density on compressive deformation behavior of aluminum cenosphere syntactic foam, *Materials Science and Engineering: A* 590 (2014) 406–415. <https://doi.org/10.1016/j.msea.2013.10.048>.
 - [44] Q. Zhang, G. Wu, Microstructure and Compression Behavior of Cenosphere Filled Aluminum Syntactic Foams, *Materials Science Forum* 706–709 (2012) 704–708. <https://doi.org/10.4028/www.scientific.net/MSF.706-709.704>.
 - [45] V. Mehta, P. Potdar, A. Joshi, Hybrid AHP-TOPSIS approach for selecting optimal aluminium matrix in casting of metal matrix composites, *OPSEARCH* (2025). <https://doi.org/10.1007/s12597-025-01079-6>.
 - [46] J. Hashim, L. Looney, M.S.J. Hashmi, Metal matrix composites: production by the stir casting method, *J. Mater. Process. Technol.* 92–93 (1999) 1–7. [https://doi.org/10.1016/S0924-0136\(99\)00118-1](https://doi.org/10.1016/S0924-0136(99)00118-1).
 - [47] D.J. Lloyd, Particle reinforced aluminium and magnesium matrix composites, *International Materials Reviews* 39 (1994) 1–23. <https://doi.org/10.1179/imr.1994.39.1.1>.
 - [48] S.B. Prabu, L. Karunamoorthy, S. Kathiresan, B. Mohan, Influence of stirring speed and stirring time on distribution of particles in cast metal matrix composite, *J. Mater. Process. Technol.* 171 (2006) 268–273. <https://doi.org/10.1016/j.jmatprotec.2005.06.071>.

- [49] V. Špada, D. Stanić, I. Brnardić, Investigation of the mechanical properties of AlSi9Cu3(Fe)/MWCNT nanocomposites prepared by HPDC, *Materiali in Tehnologije* 53 (2019) 601–606. <https://doi.org/10.17222/mit.2019.006>.
- [50] M. Žbontar, M. Petrič, P. Mrvar, The Influence of Cooling Rate on Microstructure and Mechanical Properties of AlSi9Cu3, *Metals (Basel)*. 11 (2021) 186. <https://doi.org/10.3390/met11020186>.
- [51] W. Hufenbach, M. Gude, A. Czulak, F. Engelmann, Influence of different aluminium alloys on the material properties of CF/Al-MMC manufactured by GPI method, *Kompozyty* 10 (2010) 143–148.
- [52] Z. Yu, X. Zhou, L. Jing, Theoretical prediction and design optimization of foreign-object impact resistance of graded metal foam sandwich panels, *Compos. Struct.* 379 (2026) 119975. <https://doi.org/10.1016/j.compstruct.2025.119975>.
- [53] J. Ye, A. Elsayed, T. Allam, W. Abd-Elaziem, A.R. Kamali, A.M. Abdelkader, Y. Huang, MXene-assisted interface engineering for strengthening aluminium matrix composites via high-pressure torsion, *J. Alloys Compd.* 1051 (2026) 186026. <https://doi.org/10.1016/j.jallcom.2026.186026>.
- [54] A. Hassan, I.A. Alnaser, Influence of CaCO₃ and Al₂O₃ on the Mechanical Properties of Aluminum Foam for Lightweight Structural Applications, *ACS Omega* 11 (2026) 3336–3353. <https://doi.org/10.1021/acsomega.5c10363>.
- [55] A. du Plessis, P. Sperling, A. Beerlink, W.B. du Preez, S.G. le Roux, Standard method for microCT-based additive manufacturing quality control 4: Metal powder analysis, *MethodsX* 5 (2018) 1336–1345. <https://doi.org/10.1016/j.mex.2018.10.021>.
- [56] ISO13314:2011 Mechanical testing of metals - Ductility testing - Compression test for porous and cellular metals, (2011).
- [57] D.K. Balch, J.G. O'Dwyer, G.R. Davis, C.M. Cady, G.T. Gray, D.C. Dunand, Plasticity and damage in aluminum syntactic foams deformed under dynamic and quasi-static conditions, *Materials Science and Engineering: A* 391 (2005) 408–417. <https://doi.org/10.1016/j.msea.2004.09.012>.
- [58] I.N. Orbulov, Compressive properties of aluminium matrix syntactic foams, *Materials Science and Engineering: A* 555 (2012) 52–56. <https://doi.org/10.1016/j.msea.2012.06.032>.
- [59] C. Kádár, A. Szlancsik, Z. Dombóvári, I.N. Orbulov, Monitoring the failure states of a metal matrix syntactic foam by modal analysis, *Mater. Lett.* 257 (2019) 126733. <https://doi.org/10.1016/j.matlet.2019.126733>.
- [60] B. Leveles, A. Kemény, T. Bubonyi, I.N. Orbulov, Manufacturing and Comparison of Sr Modified or Unmodified AlSi12 Eutectic Alloy Matrix Unimodal and Bimodal Composite Metal Foams, *Adv. Eng. Mater.* 24 (2022) 2100384. <https://doi.org/10.1002/adem.202100384>.
- [61] J.E. Maróti, I.N. Orbulov, Characteristic compressive properties of Al₂O₃ particle reinforced Al99.5 matrix composite foams, *Compos. Part A Appl. Sci. Manuf.* 202 (2026). <https://doi.org/10.1016/j.compositesa.2025.109468>.
- [62] P. Wang, W. Yu, J. Li, M. Zhang, Y. Bai, E. Liu, H. Hao, Mechanical enhancement of fly ash syntactic foams via synergistic effects in lattice-reinforced three-phase composites, *Mater. Lett.* 404 (2026). <https://doi.org/10.1016/j.matlet.2025.139577>.

- [63] J.E. Maróti, I.N. Orbulov, Compressive Properties of Al99.5 Matrix Syntactic Foams Reinforced by SiC Particles in the Matrix, *Periodica Polytechnica Mechanical Engineering* 69 (2025) 377–391. <https://doi.org/10.3311/PPme.42144>.
- [64] Y. Mu, Y. Duan, W. Liu, Experimental investigation of compression and energy absorption characteristics of Al/fly ash cenospheres syntactic foam, *Materialia (Oxf)*. 44 (2025). <https://doi.org/10.1016/j.mtla.2025.102596>.
- [65] J.E. Maróti, I.N. Orbulov, Characteristic compressive properties of AlSi7Mg matrix syntactic foams reinforced by Al₂O₃ or SiC particles in the matrix, *Materials Science and Engineering: A* 869 (2023). <https://doi.org/10.1016/j.msea.2023.144817>.
- [66] A. Kemény, B. Leveles, T. Bubonyi, I.N. Orbulov, Effect of particle size and volume ratio of ceramic hollow spheres on the mechanical properties of bimodal composite metal foams, *Compos. Part A Appl. Sci. Manuf.* 140 (2021) 106152. <https://doi.org/10.1016/j.compositesa.2020.106152>.
- [67] G.H. Wu, Z.Y. Dou, D.L. Sun, L.T. Jiang, B.S. Ding, B.F. He, Compression behaviors of cenosphere–pure aluminum syntactic foams, *Scr. Mater.* 56 (2007) 221–224. <https://doi.org/10.1016/j.scriptamat.2006.10.008>.
- [68] Q. Zhang, P.D. Lee, R. Singh, G. Wu, T.C. Lindley, Micro-CT characterization of structural features and deformation behavior of fly ash/aluminum syntactic foam, *Acta Mater.* 57 (2009) 3003–3011. <https://doi.org/10.1016/j.actamat.2009.02.048>.
- [69] X.F. Tao, L.P. Zhang, Y.Y. Zhao, Al matrix syntactic foam fabricated with bimodal ceramic microspheres, *Mater. Des.* 30 (2009) 2732–2736. <https://doi.org/10.1016/j.matdes.2008.11.005>.
- [70] D. Károlyi, Z. Iklódi, A. Kemény, D.B. Kincses, I.N. Orbulov, Production and Functional Properties of Graded Al-Based Syntactic Metal Foams, *Metals (Basel)*. 12 (2022) 263. <https://doi.org/10.3390/met12020263>.
- [71] B. Zhang, Y. Lin, S. Li, D. Zhai, G. Wu, Quasi-static and high strain rates compressive behavior of aluminum matrix syntactic foams, *Compos. B Eng.* 98 (2016) 288–296. <https://doi.org/10.1016/j.compositesb.2016.05.034>.
- [72] D.P. Mondal, M.D. Goel, V. Upadhyay, S. Das, M. Singh, A.K. Barnwal, Comparative Study on Microstructural Characteristics and Compression Deformation Behaviour of Alumina and Cenosphere Reinforced Aluminum Syntactic Foam Made Through Stir Casting Technique, *Transactions of the Indian Institute of Metals* 71 (2018) 567–577. <https://doi.org/10.1007/s12666-017-1211-x>.
- [73] M. Cao, F. Jiang, C. Guo, Y. Li, T. Yu, R. Qin, Interface characterization and mechanical property of an aluminum matrix syntactic foam with multi-shelled hollow sphere structure, *Ceram. Int.* 48 (2022) 18821–18833. <https://doi.org/10.1016/j.ceramint.2022.03.159>.

Supporting materials



Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Supportingmaterials.pptx](#)