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Araştırma Makalesi / Research Article

Investigation of Crushing Behavior of Polystyrene Coated Spherical Shaped Aluminum Foams

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Abstract
In this study, the crushing behavior of spherically shaped aluminum foam pieces coated with polystyrene and uncoated under compression load was investigated. The spherical shaped aluminum foam parts produced by powder metallurgy with diameters of 8 mm and 10 mm were coated with polystyrene by the injection molding process. The obtained foam elements were then subject to quasi-static compression tests at room temperature with a constant crosshead speed of 1 mm/min. According to the experimental results, polystyrene coatings increased the energy damping capacity of the foams by approximately 115% while increasing the density by about 50%.

Keywords: Spherical shaped aluminum foam, porous material, compressive properties, polystyrene.

Polistiren Kaplı Küresel Şekilli Alüminyum Köpüklerin Ezilme Davranışlarının Araştırılması

Öz
Bu çalışmada, polistiren ile kaplanmış ve kaplanmamış küresel şekilli alüminyum köpük parçaların sıkıştırma yükü altındaki ezilme davranışları incelenmiştir. Toz metalurjisi yöntemi ile üretilen 8 mm ve 10 mm çaplarındaki küresel şekilli alüminyum köpük parçalar enjeksiyon kalıplama işlemiyle polistiren ile kaplanmıştır. Üretilen köpükler daha sonra 1 mm/dak deformasyon hızında oda sıcaklığında yarı-statik sıkıştırma testlerine tabi tutulmuştur. Elde edilen deneysel sonuçlara göre, polistiren kaplamalar köpüklerin enerji sönümleme kapasitelerini yaklaşık %115 arttırırken, yoğunluğu da yaklaşık %50 oranında arttırmıştır.

Anahtar kelimeler: Küresel şekilli alüminyum köpük, gözenekli malzeme, basma özellikleri, polistiren.

1. Introduction

Metallic foams have attracted extended attention in several applications given their use as reinforcement material relative to buckling and impact in buildings and vehicles as fluid control devices, sound absorbers, and heat exchangers due to their extraordinary features [1-3]. The powder metallurgy (PM) route is an attractive method for metallic foam production since the method allows for the mass production of net-shaped geometries foams. Several studies focused on the development of aluminum (Al) foam via the PM route [4-8]. Extant studies also investigate spherical Al foam production. These materials are referred to as advanced pore morphology (APM) foam in previous studies and were developed in Germany as indicated by ref. [9]. These types of materials are considered as new with respect to cellular structures. Specifically, APM foam parts exhibit a closed porous structure and are manufactured by using a powder compression method. The precursor material prepared before the forming process is cut into small pieces and placed in a furnace for foam formation without a foaming mould [10]. The density of the produced foams ranges between 500 kg/m^3 and 1,000 kg/m^3 depending on its size [11].

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An extremely important feature of Al foam is that it displays unique behavior under compression loadings. Thus, Al foam is eligible for use in energy absorption. Additionally, APM foam exhibits behavior similar to that of conventional Al foam under compressive forces [12]. Furthermore, APM foam elements include a wide range of possible areas of use. An extremely important advantage of the material involves its ability to absorb impact energy and its use as a filling material for hollow parts with complex shapes to improve its strength [11]. For example, a hollow auto part (such as A-pillar) can be easily filled with these types of material. Therefore, APM foam elements exhibit resistance to forces applied to the parts without considering their direction due to their spherical shape. Recent studies focus on the structure-property relations of the APM foam elements [11, 13-15]. Vesenjak et al. [11] acquired data on the pore size and image of APM foam elements via analysis through a computed micro tomography scan. Conversely, Ulbin et al. [13] explored the impact of silicon as an alloy on the internal structure of APM foam elements by using a new approach for the data obtained with a similar method.

Studies on improvements in mechanical properties of single APM foams are considerably limited. Vesenjak et al. [12] explored the deformation behavior of the composite APM foam structures coated with an epoxy matrix and a single foam particle under quasi-static compression loads. Nevertheless, other studies focused on the adhesive used in the bonding of the foam pieces and the adhesive coating thickness for the hydrostatic and uniaxial compression results of the structures based on APM foam particles [10, 12, 16]. These studies involved single foam pieces that were bonded to each other and coated. As widely known, Al foam pieces manufactured with the PM approach consist of a fully porous structure covered with fine surface skin [17]. Specifically, errors (such as cracks and defects) initiated in the cell walls can also correspond to a case for the surface layer. This may lead to a decrease in the mechanical properties of the foam pieces. Hence, a surface coating covers the surface cracks to improve the mechanical properties of the foam pieces. In this study, single APM foam pieces were coated with polystyrene via injection moulding. Polystyrene is a material that is commonly used in several industries including construction and packaging with a wide range of uses [18]. The material is significantly inexpensive and is also used as a light construction material [19, 20]. These types of materials are considerably balanced and resistant relative to decomposition due to the available phenyl group and carbon-carbon bonds [21]. The study proposes the use of novel hybrid APM foam pieces and explores their deformation behavior under compressive loads.

2. Material and Method

2.1. Production of spherical shaped aluminum foams

The powder metallurgy process is successfully used to produce three-dimensional net-shaped foam parts. The manufacturing procedure consists of powder compaction, extrusion, and rolling of AlSi7 alloy with Si (7 wt. % as an alloying element) and TiH_2 (1 wt. % as a foaming agent) to obtain foamable precursor material. Detailed information on the foamable material production is given in [22]. Subsequently, the precursor material was cut into small parts of approximately $5 \times 5 \times 3$ mm^3 in size (Figure 1a). These samples were placed in a two-part foaming mold (Figure 1b). Subsequently, the foaming mold was placed in an oven at 710 ^{o}C, and foaming was performed (Figure 1c). Finally, the net-shaped foam with different cross-sections was obtained (Figure 1d). The foam samples were obtained by means of free-form foaming in previous studies. Spherical shapes of the precursor samples were obtained via surface tension in a continuous belt furnace in the foaming process. However, the samples are not exactly spherical due to the melting foam that is deformed due to gravitational forces [10, 23]. The problem was solved when the foaming process was conducted in the mould as schematically shown in Fig. 1b. Thus, foams with better spherical shapes were obtained, and the size control was easily performed. Additionally, the surface roughness was observed as lower than that of the free-foaming. Thus, the notch effect is reduced during the deformation.

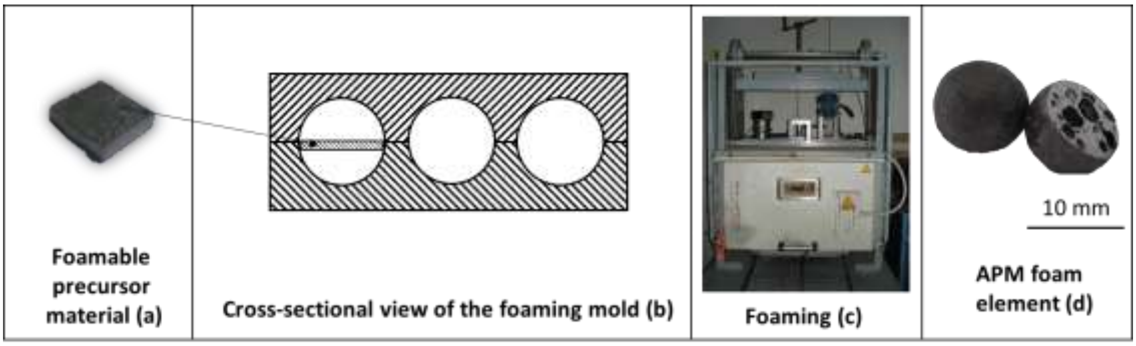

Figure 1. Spherical shaped aluminum foam production stages; (a) foamable precursor material, (b) foaming mould, (c) foaming furnace, (d) foam element

2.2. Injection moulding processing

The injection moulding experiments were conducted on an industrial injection moulding machine. In the experiments, polystyrene granules were used as a coating material (Figure 2a). Polystyrene granules exhibit an average particle size of 3.0 mm and a density of 0.90–0.92 g/cm^3 at room temperature. Polystyrene granules were melted under the effects of heat (200 °C), and the melt was then injected forward into the moulds with diameters of 8 mm and 10 mm. The moulds were used in the foaming process since the injection mould was used at 20 °C. Additionally, spherical shaped aluminum foam elements with diameters of 8 mm and 6 mm were used to produce moulded spherical shaped aluminum foams with diameters of 10 mm and 8 mm (Figure 2b), respectively. Thus, the deformation behavior of injection coated spherical shaped aluminum foam and uncoated foam elements with the same diameter under a compressive load is compared.

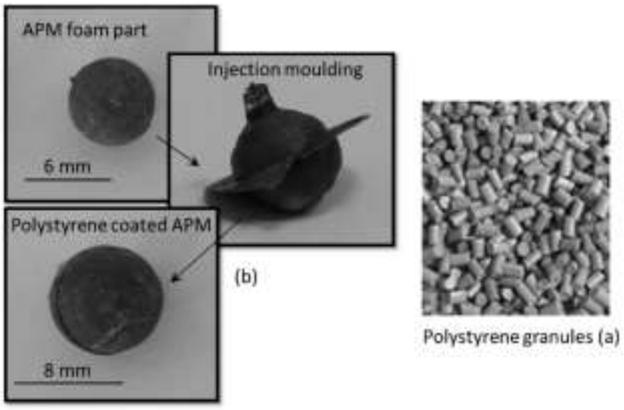

Figure 2. Polystyrene granules (a) and injection moulded spherical shaped aluminum foam (b)

2.3. Compressive test

Quasi-static compression tests were performed at room temperature on a universal testing machine (Instron 3369) with a constant crosshead speed of 1 mm min^{-1}, and the load-displacement curves were recorded in a computer. Two types of coated and uncoated spherical shaped aluminum foam samples with diameters of 8 mm and 10 mm were tested. Each sample was placed between two press plates. During the tests, the bottom press plate was stationary while the upper press plate was moved to apply and measure the compressive force. A minimum of three or more samples for each configuration was investigated in the experiments.

3. Results and Discussion

Figure 3 exhibits the load-displacement curves of the polystyrene coated and uncoated spherical shaped aluminum foam elements with varying densities with a diameter of 10 mm. These curves are obtained from the compressive tests and reveal the strength differences between samples. However, low-density differences between samples may lead to low deviations and the load-displacement curves available in both graphs reflect the crushing behavior of porous materials. In contrast to the stress and strain data, the data obtained was not standardized for the sample size. The available curves consist of a linear–elastic region, a plateau region, and a densification region [15]. Specifically, the plateau forces of the polystyrene coated spherical shaped aluminum foam elements exceed those of uncoated spherical shaped aluminum foam elements. The results indicate that the polystyrene structure exhibits rigid behavior during deformation. This ensures that the spherical shaped aluminum foam element is sufficiently strong. A comparison of the load-displacement curves of coated and uncoated spherical shaped aluminum foam (dark black lines) indicates a significantly low difference in the linear elastic region while the difference significantly increased with increases in the displacement. In the 10% deformation region, the plateau force of the polystyrene coated spherical shaped aluminum foam is approximately 710 N while it is approximately 460 N for the uncoated spherical shaped aluminum foam. The pores available in the internal structure of the sample collapse after the linear–elastic region, and thus irregularities may be observed in the outer surface of the spherical-shaped aluminum foam elements. An identical outcome was also observed in other studies [10]. The irregularities take the form of cracks in a higher level of deformation that eventually leads to the collapse of the outer surface. Given the use of polystyrene coating, stress formed due to the deformation does not contribute to crack formation. An increase in the force was naturally observed.

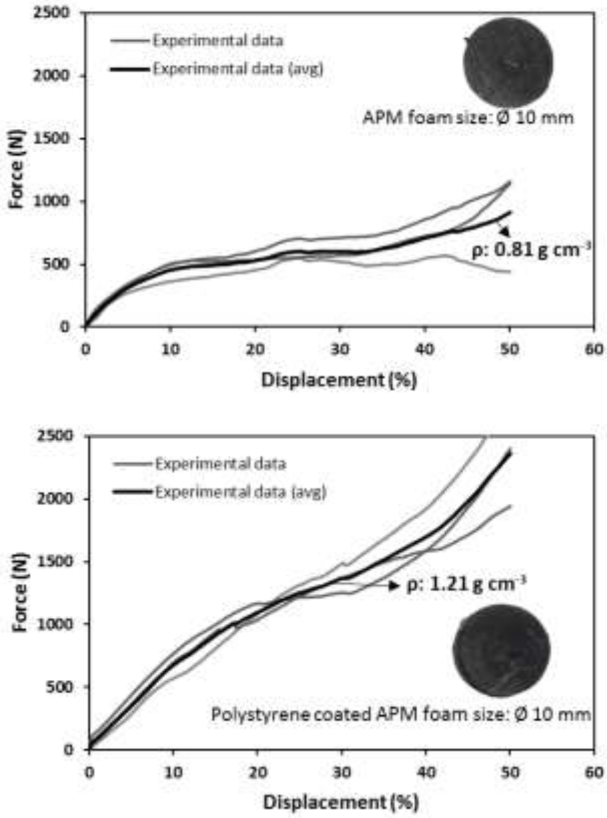

Figure 3. Behavior of polystyrene coated and uncoated spherical shaped aluminum foam elements (Ø:10 mm) under a quasi-static compressive load

Figure 4 shows the compression status of polystyrene coated and uncoated spherical shaped aluminum foam with a diameter of 10 mm during deformation. As shown in the figure, the contact area between press plates and the spherical samples depends on the sample deformation. An increase in the deformation causes the press plates flatten the spherical foam samples. Cracks were observed especially for the single spherical shaped aluminum foam elements at 30% deformation. However, crack formation was observed at 40% deformation for polystyrene coated spherical shaped aluminum foam samples. Color changes are observed relative to the stress intensity for these types of material at the outer surface layers. This indicates increased stress at the sample surfaces. Similar circumstances (such as crack formation) may be observed in the case with lower stress levels for the samples as a whole. However, it may not be possible to observe the cracks based on the geometrical shape caused by the deformation during the compression test.

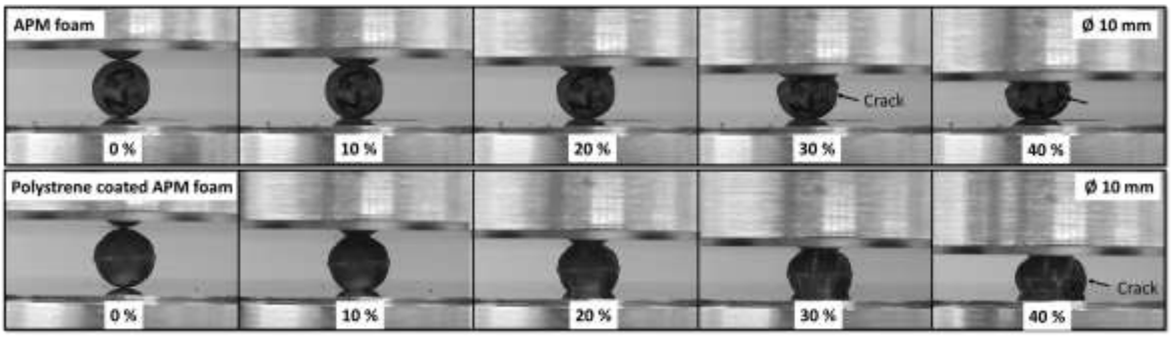

Figure 4. Deformation sequence of polystyrene coated and uncoated spherical shaped aluminum foam (Ø:10 mm) subjected to uniaxial compression

Figure 5 shows the scanning electron microscope (SEM) images of the cross-section of polystyrene coated spherical shaped aluminum foam (Ø 10 mm). The images indicate the presence of a successful coating on the outer surface of the foam samples (with a thickness of 1 mm). However, polystyrene could penetrate weak or defective points on the outer surface skin and cell wall thereby filling the pores during the injection process. Thus, an increase in the density and compressive strength of the spherical-shaped aluminum foam parts was observed. The bending resistance of the cell walls of the spherical-shaped aluminum foam increased with polystyrene.

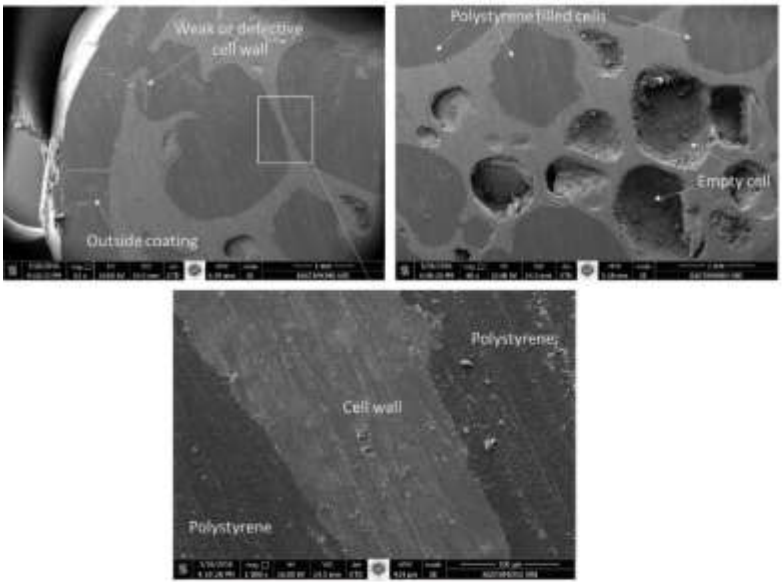

Figure 5. Scanning electron microscopy of the polystyrene coated spherical shaped aluminum foam element

Figure 6 shows the load-displacement curves of the polystyrene coated and uncoated spherical shaped aluminum foam elements with varying densities with a diameter of 8 mm. The graphs indicate that low-density differences lead to low deviations as in the case for load-displacement curves of coated and uncoated spherical shaped aluminum foam with diameters of 10 mm. The plateau forces of the polystyrene coated spherical shaped aluminum foam elements are higher than those of the uncoated spherical shaped aluminum foam elements. The results indicate that the polystyrene structure exhibits rigid behavior during deformation that ensures sufficient strength for the spherical shaped aluminum foam element as in the case for samples with diameters of 10 mm. A comparison of the average load-displacement curves of coated and uncoated spherical shaped aluminum foams indicates a significant change in force in the case with increased displacement. At the 10% deformation region, the limit force of the polystyrene coated spherical shaped aluminum foam is approximately 760 N while it is approximately 302 N for the uncoated spherical shaped aluminum foam. Figure 7 shows the compression status of polystyrene coated and uncoated single spherical shaped aluminum foam during the deformation. As shown in the figure, the contact area between press plates and the spherical samples depends on the sample deformation. An increase in the deformation causes press plates to flatten the spherical foam samples.

Thus, a higher increase is observed in deformation resistance relative to compressive loads and force levels of the samples with higher diameters (10 mm). A similar finding is observed in [23]. Higher density leads to an increase in the force level for samples with fixed volumes. Specifically, the polystyrene coating increases the sample density. The cross-section of the samples in the force direction is not uniform. Spherical shapes assume an elliptic form with deformation. The spherical shaped aluminum foam elements consist of a closed outer surface as in the case for conventional Al foam. The regions involve a density gradient from the inner layer to the outer layer. Structural resistance during deformation is expected from these regions. A comparison of the structural rigidity of samples with diameters of 10 mm and 8 mm indicates an increase in the structural rigidity for polystyrene coated samples with both diameters. The presence of polystyrene on the surface of the spherical-shaped aluminum foam as a coating material and in the internal microstructure of spherical shaped aluminum foam can explain this difference.

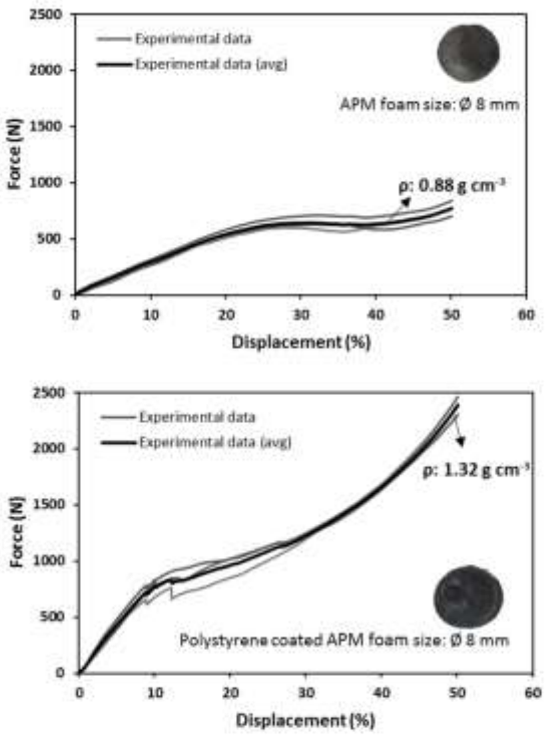

Figure 6. Behavior of polystyrene coated and uncoated spherical shaped aluminum foam elements (Ø:8 mm) under a quasi-static compressive load

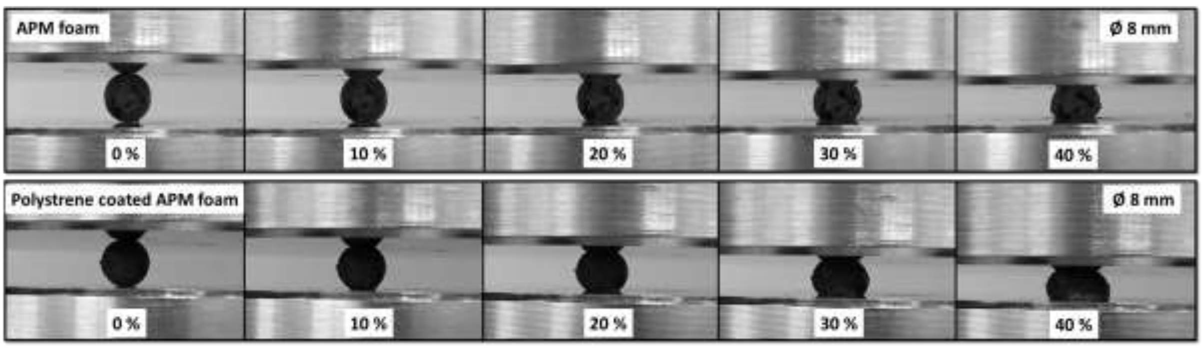

Figure 7. Deformation sequence of polystyrene coated and uncoated spherical shaped aluminum (Ø:8 mm) subject to uniaxial compression

Figure 8 shows the total energy absorbed by the spherical foams. The total energy absorbed is calculated by using the area available under the load-displacement curve. The graph indicates that the polystyrene coating significantly impacts the energy absorption capacity of the spherical-shaped aluminum foam. Polystyrene coated spherical shaped aluminum foam with a diameter of 10 mm is the sample with the highest total absorbed energy (6.03 J). Conversely, uncoated spherical shaped aluminum foam with an identical diameter results in energy absorption of 2.8 J. The energy absorbed by the coated sample is higher than that absorbed by the uncoated sample by a factor of two. The total energy absorption values of coated and uncoated spherical shaped aluminum foam with a diameter of 8 mm are 4.66 J and 2.04 J, respectively. Similarly, the difference between the energy absorption values of both samples exceeds by a factor of two. It is widely known that the relative density significantly affects the mechanical properties of the metallic foam. Higher mechanical responses are reported for materials with higher relative density values [1]. As observed in the load-displacement graphs in Figure 3 and Figure 6, polystyrene coated spherical shaped aluminum foam samples exhibit higher density. Therefore, their energy absorption level exceeds that of uncoated spherical shaped aluminum foam. Nevertheless, an increase in the energy absorption capacity is expected with increases in the plateau stress [24]. Thus, the energy distribution of the metal foam under compressive forces is with respect to the friction that is formed given the contact and collapse mechanism of the cell walls [25]. The polystyrene filling of the spherical-shaped aluminum foam pores increases the energy distribution limiting fracture, buckling, and bending of cell walls during the deformation.

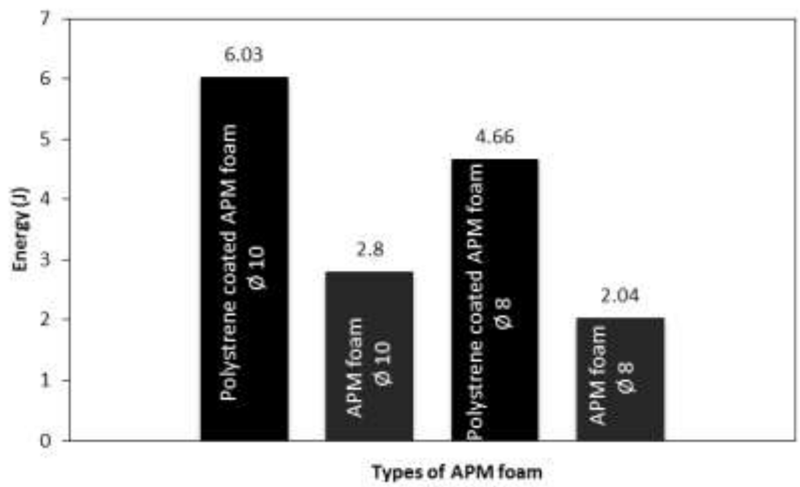

Figure 8. Energy absorption capabilities of the spherical-shaped aluminum foam elements

4. Conclusion

This study involved evaluating the behavior of single polystyrene coated and uncoated spherical shaped aluminum foam elements via experimental compressive testing. The spherical shaped aluminum foam elements exhibited characteristic cellular material behavior. Larger spherical shaped aluminum foam elements (coated and uncoated) i.e. Ø 10 mm, could sustain higher compressive loads. The coated spherical shaped aluminum foam elements exhibited higher energy absorption capacity that was approximately twice that of the uncoated spherical shaped aluminum foam elements. Furthermore, it was indicated that polystyrene skin significantly contributes to the mechanical strength of spherical shaped aluminum foam elements.

Author' Contributions

All contribution belongs to myself in the article

Statement of Conflicts of Interest

There is no conflict of interest among the authors

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

References

[1] Bafti H., Habibolahzadeh A. 2013. Compressive properties of aluminum foam produced by powder-carbamide space route. Materials and Design, 52: 404-411.

[2] Jeon I., Asahina T. 2005. The effect of structural defects on the compressive behavior of closed-cell Al foam. Acta materialia, 53: 3415-3423.

[3] Sun D.X., Zhao Y.Y. 2003. Static and dynamic energy absorption of Al foams produced by a sintering and dissolution process. Metallurgical and Materials Transactions B, 34: 69-74.

[4] Duarte I., Oliveira M. 2012. Aluminium alloy foams: production and properties. In Powder metallurgy, InTech., 47-72.

[5] Rack A., Helwig H.M., Bütow A., Rueda A., Matijasevic-Lux B.B., Helfen L., Goebbelse J., Banhart J. 2009. Earlypore formation in aluminium foams studied by synchrotron-based microtomography and 3-D image analysis. Acta Materialia, 57: 4809-4821.

[6] Mukherjee M., Garcia-Moreno F., Banhart J. 2010. Solidification of metal foams. Acta Materialia, 58: 6358-6370.

[7] Duarte I., Banhart J. 2000. A study of aluminium foam formation-kinetics and microstructure. Acta materialia, 48: 2349-2362.

[8] Koizumi T., Kido K., Kita K., Mikado K., Gnyloskurenko S., Nakamura T. 2011. Foaming agents of powder metallurgy production of aluminum foam. Materials transactions, 52: 728-733.

[9] Stöbener K., Baumeister J., Rausch G., Rausch M. 2005. Forming metal foams by simpler methods for cheaper solutions. Metal Powder Report, 60: 12-16.

[10] Stöbener K., Lehmhus D., Avalle M., Peroni L., Busse M. 2008. Aluminum foam-polymer hybrid structures (APM aluminum foam) in compression testing. International Journal of Solids and Structures, 45: 5627-5641.

[11] Vesenjak M., Borovinšek M., Fiedler T., Higa Y., Ren Z. 2013. Structural characterisation of advanced pore morphology (APM) foam elements. Materials Letters, 110: 201-203.

[12] Vesenjak M., Gačnik F., Krstulović-Opara L., Ren Z. 2011. Behavior of composite advanced pore morphology foam. Journal of Composite Materials, 45: 2823-2831.

[13] Ulbin M., Borovinšek M., Higa Y., Shimojima K., Vesenjak M., Ren Z. 2014. Internal structure characterization of AlSi7 and AlSi10 advanced pore morphology (APM) foam elements. Materials Letters, 136:416-419.

[14] Fiedler T., Sulong M.A., Vesenjak M., Higa Y., Belova I.V., Oechsner A., Murch G.E. 2014. Determination of the thermal conductivity of periodic APM foam models. International Journal of Heat and Mass Transfer, 73: 826-833.

[15] Vesenjak M., Gačnik F., Krstulović-Opara L., Ren Z. 2015. Mechanical properties of advanced pore morphology foam elements. Mechanics of Advanced Materials and Structures, 22: 359-366.

[16] Lehmhus D., Baumeister J., Stutz L., Schneider E., Stöbener K., Avalle M., Peroni L., Peron M. 2010. Mechanical characterization of particulate aluminum foams strain-rate, density and matrix alloy versus adhesive effects. Advanced Engineering Materials, 12: 596-603.

[17] Banhart J. 2001. Manufacture, characterization and application of cellular metals and metal foams. Progress in Materials Science, 46: 559-632.

[18] Marsh K., Bugusu B. 2007. Food packaging roles, materials, and environmental issues. Journal of Food Science, 72 (3): 39-55.

[19] Mbadike E.M., Osadebe N.N. 2012. Effect of incorporating expanded polystyrene aggregate granules in concrete matrix. Nigerian Journal of Technology, 31: 401-404.

[20] Kuhail Z., Shihada S. 2003. Mechanical properties of polystyrene light weight concrete. Journal of the Islamic University of Gaza, 11: 93-114.

[21] Chaukura N., Gwenzi W., Bunhu T., Ruziwa D.T., Pumure I. 2016. Potential uses and value-added products derived from waste polystyrene in developing countries: A Review. Resources Conservation and Recycling, 107: 157-165.

[22] Uzun A., Turker M. 2015. The investigation of mechanical properties of B_4C-reinforced AlSi7 foams. International Journal of Materials Research, 106: 970-977.
[23] Sulong M.A., Vesenjak M., Belova I.V., Murch G.E., Fiedler T. 2014. Compressive properties of Advanced Pore Morphology (APM) foam elements. Materials Science and Engineering A, 607: 498-504.
[24] Jeenager V.K., Pancholi V. 2014. Influence of cell wall microstructure on the energy absorption capability of aluminium foam. Materials and Design, 56: 454-459.
[25] Guo C., Zou T., Shi C., Yang X., Zhao N., Liu E., He C. 2015. Compressive properties and energy absorption of aluminum composite foams reinforced by in-situ generated MgAl2O4 whiskers. Materials Science and Engineering A, 645: 1-7.