Metallic Foams, New Generation of the Environmental Friendly Materials

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Abstract

Metallic foams or Metfoams are a new class of advanced materials in environmental friendly materials group. These materials are the family of the cellular materials with low densities and novel physical, mechanical, thermal, electrical and acoustic properties. They are recyclable and nontoxic. They hold particular promise for market penetration in applications in which several of these features are exploited simultaneously. Recent technological advances in the field of metallic foams have led to the development of a wide range of processing techniques for the open, as well as closed cell morphologies. The processing route has to be decided on the basis of the cost of production, material properties, and the intended applications of the final product.

Keywords: Metallic Foams, Environmental Friendly Materials, Advance Materials.

1. Introduction

Cellular materials are widespread in everyday life and are used for cushioning, insulating, damping, constructing, filtering purposes and many other applications. Highly porous materials are also known to have a high stiffness combined with a very low specific weight.

For this reason cellular materials frequently occur in nature as constructional materials (e.g. woods and bones).

The fact that even metals and metallic alloys can be produced as cellular solids or metal foams is not as well-known as the possibility to foam more traditional engineering materials such as polymers, ceramics or glass. In order to achieve this goal, metal foams have been developed [1].

Metal foams are simulated with their structure naturally porous, cellular and spongy materials like wood, sponges, bones, corals, etc. Structure of the metal foams is porous in the range from 40 % to 90 %. Till today metal foams have been produced on the basis of aluminum (Al), nickel (Ni), magnesium (Mg) and titanium (Ti) copper (Cu) gold (Au) steel and stainless steel alloys [2-4]. Metal foams have many unique properties that make them the environmental friendly materials, using these materials in construction and component of the engineering structure helps to save energy and less pollution to the environment, therefore the metallic foams are attractive materials for components of machines, vessels, car body elements and etc. Foams find applications in aircraft designs, civil engineering and road infrastructure. Their low density makes foams an ideal filler material for layered structures of high stiffness.

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With low thermal conductivity, foams can be used as heat insulators, while vibration absorbing property makes foams adequate for vibration damping linings. Under load foams are subject to substantial deformations, the characteristic that leads to such applications as impact energy absorbers, explosion impact reducers, or packaging. Cellular materials may have either isotropic or anisotropic properties. There are following applied definitions for metal foams [4-7]:

a- Porous materials, whose structure can be described as geometrically disordered distribution of pores in a metal matrix;

b- Metallic material containing a large number of pores filled with gas in its volume.

The structure, size of the cells and the chemical composition are the most important factors that determine the properties, and thus the possible areas of usage.

Metal foams with open cells or closed cells can be produced. Favorable properties of metal foams are: extremely low density, high specific stiffness, very good impact energy and electromagnetic waves, good heat insulation, very good sound absorption, fire resistance, recyclability, etc. [8].

This kind of morphology is also known as cellular solid structure. There are three variants of cellular solids: open cell, closed cell structures, and a combination of both [9-11].

Closed-cell materials provide good mechanical properties but do not allow access to their internal surface.

Therefore, they are mostly used in structural, load-bearing applications. In contrast, open porosity is generally required for functions associated with the interior of the material.

Accordingly, open-cell foams are mostly used in functional applications where loadbearing capability is not the primary goal [10-13].

Fig. 1. shows the representative structures of closed cell and open cell of the metallic foams.

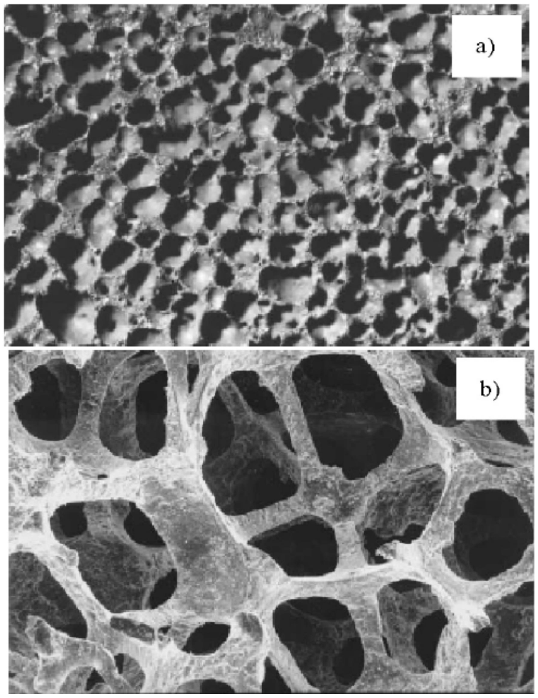

Fig. 1. Representative structures of metallic foams [13]. a) closed cell, b) open cell.

The properties of metal foams depend upon the properties of the base material, the relative density, cell topology and the production process. When defining the properties it is important to distinguish the difference between the properties of the metal foam and the properties of the base material [14]. Beyond this, foam properties are influenced by structure, particularly by anisotropy and by defects of the cells. Cells can be of irregular shape, with differences in size. Cell walls are often broken, which considerably reduces the mechanical properties of the foam and porosity varies ten or more percent. The key properties of metal foam are as follows [14-16]:

-Low density

-High compression strengths

-Good energy absorption

-Low thermal conductivity

A primary feature of metal foams is high porosity, usually ranging between 75 and 95%. Consequently, foam density makes up 5-25% of the density of metal the foam is made of.

The Potentials of the applications for metal foams are as follows [16-20]:

-Lightweight structures: Excellent stiffness-to-weight ratio when loaded in bending

-Sandwich cores: Metal foams have low density with good shear and fracture strength/ Strain isolation Metal foams can take up strain mismatch by crushing at controlled

-Mechanical damping: The damping capacity of metal foams is larger than that of solid metals by up to a factor of 10

-Vibration control: Foamed panels have higher natural flexural vibration frequencies than solid sheet of the same mass per unit area

-Acoustic absorption: Reticulated metal foams have sound-absorbing capacity

-Energy management: Metal foams have exceptional ability to absorb compact or light energy at almost constant pressure

-High-temperature capability: Ability to absorb impact at constant load, coupled with thermal stability above room temperature

-Artificial wood: Metal foams have some wood-like characteristics: light, stiff, and ability to be joined with wood screws

-Thermal management: Open-cell foams have large accessible surface area and high cell-wall conduction giving exceptional heat transfer ability/ High thermal conductivity of cell edges together with high surface area quenches combustion/ metallic foams are non-flammable; oxidation of cell faces of closed-cell aluminum foams appears to impart exceptional resistance to direct flame

-Biocompatible inserts: The cellular texture of biocompatible metal foams such as titanium stimulates cell growth

-Filters: Open-cell foams with controlled pore size have potential for high-temperature gas and fluid filtration

-Electrical screening: Good electrical conduction, mechanical strength and low density make metallic foams attractive for screening

-Electrodes and catalyst carriers: High surface/volume ratio allows compact electrodes with high reaction surface area

-Buoyancy: Low density and good corrosion resistance suggest possible floatation applications

2.Type of metallic foams

The metallic foams classified by application in two categories as [19-21]:

a- Structural applications

b- Functional applications

Metallic foams used widely for structural applications. The advantages of metallic foams in structural applications are [22-24]:

• Metallic foams are ideal to be used in energy dissipating devices due to their capacity for absorbing large amounts of energy at lower stress levels. Moreover, because of their low specific weight, they do not add undue weight to the structure.

• Metallic foams have a high stiffness-to-weight ratio and therefore can be used as the stiffener in the members while total mass of the structure will not be changed significantly.

• Metals in the structures can be replaced with metal foams, creating members with similar weight but much lower local slenderness ratios.

• Some kinds of the metal foams such as steel foams show some evidences for weldability to other steel components. This is one of the benefits of using steel foams for enhancing ductility in comparison with other methods such as shape memory alloys.

The metallic foams structural application classification as[25-27]:

-Closed-cell metallic foams: Most of the recent activities on closed-cell metallic foams have focused on the development of nonferrous metals such as aluminum alloys based foams.

This is principally because the melting point of aluminum is low; the processing simple and aluminum foams provide favorable mass-specific mechanical properties. Efforts to develop foams with other metals are nevertheless ongoing, including steel, superplastic zinc, magnesium and even heavy elements such as gold.

-Iron based materials: Iron based foams have been considered as an alternative to aluminum foams, because steel has higher strength, higher capability to absorb energy and is generally cheaper than aluminum.

-Metal foam-based composites: Combining metal foams with other materials offers unique opportunity to tailor material properties.

The potential for improvements is still large as demonstrated by the combination of aluminum foam and glass-fiber reinforced polymer composites and aluminum alloy sheets or by composites containing aluminum foam spheres bonded together with a polymeric adhesive.

-Amorphous metallic foams: Beside reducing density, pores in amorphous metals improve significantly their compressive ductility, from near zero in the bulk to values as high as 80% for cellular architectures.

This is explained by shear-band interruption by individual pores at low porosities and stable plastic bending of thin struts at higher porosities.

-Metallic hollow spheres: Composites and syntactic structures have also been developed with hollow spheres for structural applications , hollow Cu_2O and NiO nanoparticles via the oxidation of Cu and Ni nanoparticles is one of the new materials in this group.

-Wire mesh structures: Recently, a technique to fabricate multi-layered Kagome truss periodic structures named 'Wire-Woven BulkKagome (WBK) truss' has been developed.

The fabrication is based on the assembly of helical wires in six directions.

The structures are periodic and very uniform, have good specific properties and are highly permeable. Different materials have been produced with this process so far such as: steel, aluminum and titanium. The structural metallic foams are used at ship building industry, aeronautic industry, railway industry, automotive industry, building industry and sport equipment.

Functional applications of the metallic foams are based on the special physical, chemical and mechanical properties.

The metallic foams functional application classification as [27-30]:

-High temperature resistant materials: recently development of metallic foams for high temperature filtration and solid-oxide fuel cells operating at elevated temperatures such as: Fe-Ni-Cr-Al, Ni-Cr-Al alloys.

-Materials with elongated pores: Important infrastructure and research activities have been set up recently the Various materials such as :Cu, Ni, Mg, Al, Si, TiAl, alumina.

-Biomaterials: Porous coatings have been initially proposed at the end of the 1960's to overcome problems encountered with bone cement.

The goal was to produce a rough surface that increases the friction forces between the implant and the surrounding bone thus providing better initial stability to the implant.

After implantation, the bone grows into the porous surface and helps to secure the long term stability of the implant. These coatings are now extensively used in various orthopedic applications.

-Nanoporous materials: These materials, characterized by very high specific surface area and fine pore size, have been considered in electrodes, catalyst, sensors, actuators and filtration applications.

Fig. 2. shows the applications metallic foams according to the degree of openness needed and whether the application is more functional or structural.

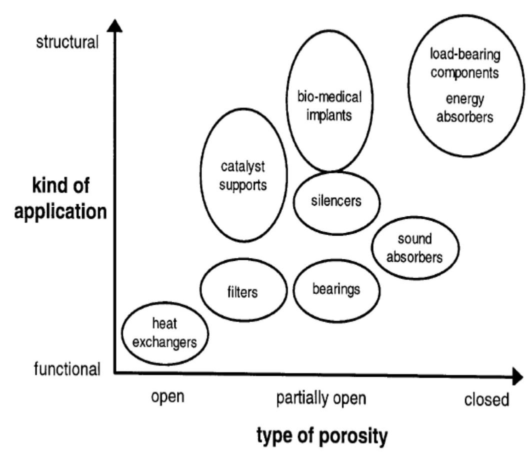

Fig. 2. Applications of the metallic foams [30].

3. Production Methods

The various production methods of the metallic foam are shown in Fig. 3..

Fig. 4. shows the ranges of cell size, cell type (open or closed), and relative densities that can be produce with different methods.

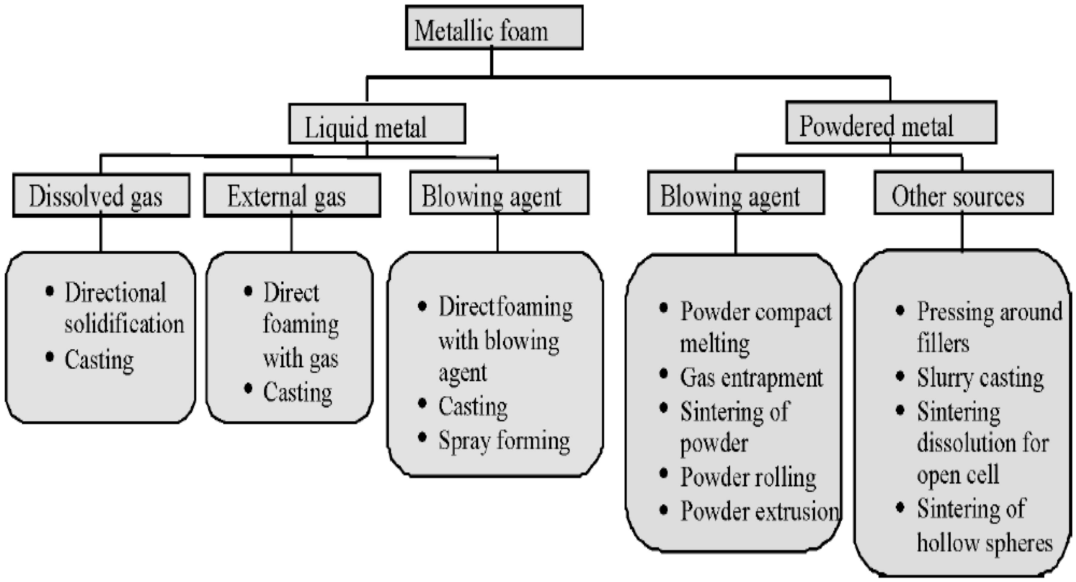

Fig. 3. The various production of the metallic foams [31].

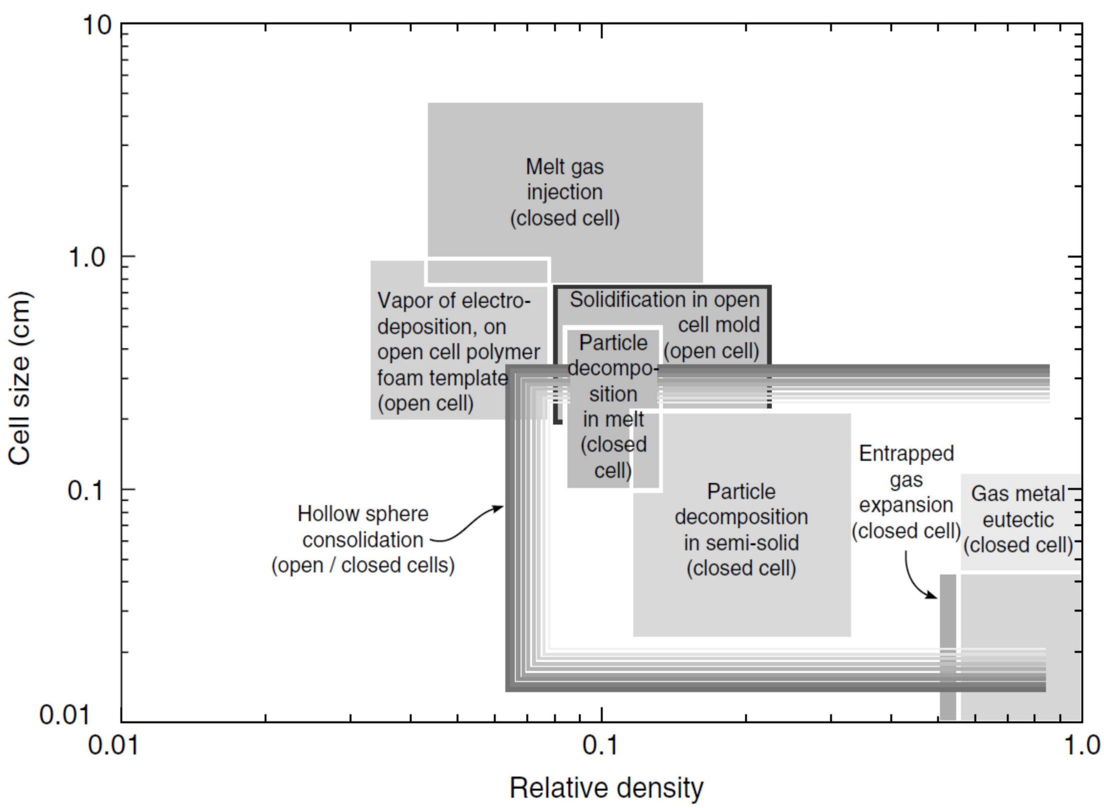

Fig. 4. Cell size and relative density for the different metallic foam production methods [32].

This indicates the possibility to produce metallic foams in two materials states: liquid metal and powdered metal.

As we know that the basic aim of foam processing is to incorporate large and uniformly distributed gas pores in the metallic materials.

The external gas source means the melt has to be foamed with the help of gases such as air, nitrogen or argon. Dissolved gases lead to foaming because they precipitate from the melt during solidification and if they are not allowed to escape, they will give rise to a foamed structure [31,32].

The gas source from a blowing agent implies decomposition of a chemical giving rise to a gaseous product.

The gas generated from this source is entrapped in liquid or semi-solid material culminating into metallic foam. In the following sections, we will review various processes where different gas sources or other materials are utilized to produce cellular materials [32].

-Dissolved gas sources: In general, gases are dissolved in liquid metal depending upon the temperature and externally applied pressure. Such metals with absorbed gases in liquid state eventually undergo a eutectic reaction to a two phase system (gas + liquid) as the temperature is lowered.

A co-ordinated effort to entrap the gas during solidification leads to a porous structure [31-33].

-External gas source: This process consists in the blowing of liquid metal by gases and to ascertain uniform distribution of large gas pores in the liquid metal [31,32].

-Blowing agent as gas source: As an alternative to the direct foaming of melt by an external gas source, a blowing agent can be added to a viscous melt, which decomposes on heating and releases gas leading to the foaming process. Spray forming is a technique utilized for the production of alloys and composites with fine and equiaxed grain, low oxide content, and low porosity compared to cast alloys. The technique consists of two distinct but integral processes of melt atomization into micron-sized droplets and their subsequent deposition onto a substrate [32, 33].

-Blowing agent as gas source: The powder compact melting process comprises several steps, such as blending of metal or alloy powder with the foaming agent, compaction of powder blend, deformation or working and foaming. Compaction of powders can be accomplished in several ways, such as cold compaction followed by sintering, hot pressing, powder rolling and powder extrusion [33, 34].

The fundamental aim of all such processes up to the foaming step is to form a very dense foamable precursor with uniform distribution of the embedded blowing agent and without any notable residual open porosity. The foamable precursor is subsequently heated to just below the melting point of the matrix material to affect the foaming process. Where a purposefully incorporated inert gas source is used for the foam genesis instead of a blowing agent. In this process, the material to be foamed is canned and degassed, followed by refilling with an inert gas at a high pressure and sealing. To get a uniform distribution of the entrapped compressed gas in the powder compact, the sealed system is isostatically hot-pressed. Secondary processing of such compacts involves annealing the compact at around 0.6Tm. The softening of the metal and a simultaneous increasing of pressure of the entrapped gases leads to creeping of the material [34,35].

4. Future of Metallic Foams

The metallic foams Market revenue is set to rise from USD 75 million in 2019 to around USD 100 million by 2025, according to a 2019 Global Market Insights, Inc. report. Rising initiatives and industry trends to reduce the vehicle weight will drive the metal foam market demand in the automotive industry.

Increasing usage of metal foam to manufacture the lightweight vehicles to reduce fuel consumption will drive product demand. Metal foams are used as sound dampers, firewall material in vehicle body parts & structure as it offers thermal insulation, heat exchanger and fire resistance benefits. Moreover, increasing consumer shift toward electric cars will increase the metal foams demand, which will further spur the product market in the next few years [36-38].

In general, an electric vehicle's battery produces heat & voltage and that need to be covered with a special material to ensure no power surges. With the continuing drive to keep vehicle weight to the minimum, metal foams offer a clear advantage over the traditional mechanical fixings. Additionally, increasing investments by automotive companies in hybrid and electric cars will increase the use of specialty metal foam. In 2017, Volvo announced that it is planning to manufacture only hybrid and electric cars by 2019. In July 2018, there is an increase of 66% in sales of plug-in vehicles from July 2017. China accounted for around 51% of the overall volume of plug-in vehicles and reached a peak share of 4.8% plug-ins in the world's largest car market. Mass production and critical production process are some restraining factor for metal foam market growth in coming.

The metal foam production with desirable properties is slightly hard and acts as a restraint for entire market growth [36-39].

Global metal foam market is divided into product, material and end-use sector. The product segment further categorized into closed and open cell. Among these products, closed cell metal foam will witness the growth with more than 4% CAGR between 2019 to 2025.

Impact absorption, heat & fire resistance are some characteristics of the products, which makes it perfect for building & construction and automotive applications [38-40].

Based on material, global market is segmented titanium, copper, aluminum, zinc, and others.

The other metal foam materials comprise nickel, magnesium, cadmium, steel, etc.

Among these materials, copper is likely to growth with over 3.5% CAGR in future as it is ideal for sound and vibration absorption, heat exchangers[39,40].

Based on end-use sector, global metal foam market is divided into energy, building & construction, automotive, healthcare, automotive and others.

The other end-use sectors include railways, consumer goods, marine, etc.

From this end-use, building & construction is likely to grow with more than 5% CAGR between 2018 to 2025. Growth in building & construction sector in various countries of Middle East and Africa along with India due to rapid population growth is one of the major driving factors for metal foam demand [38, 40].

5. Conclusions

The metallic foams as advanced materials develop by engineering as the new generation environmental friendly materials and today used in numerous industrial applications as lightweight structures, biomedical implants, filters, electrodes, catalysts, heat exchangers and etc.

Using these materials in construction and component of the engineering structure helps to saving energy and less pollution to the environment.

The most commercially available metallic foams are based on ferrous (steel, stainless steel) and nonferrous (magnesium, copper, titanium, aluminum, nickel and gold) metals.

Open and closed pore morphologies can be achieved. Cost reduction is also an important issue in current developments. Using cheaper starting materials, omitting or combining processing steps, and reducing scrap during production are the usual strategies.

With some of these improvements coming into reality, there is some hope that in the very near future industrial mass market applications will be realized which in turn will trigger other use of metallic foams.

This activity by materials engineering to be achieving integrated solutions that ensure the metallic foams can be produced economically with the required quality and reproducibility and that their integration into engineering systems makes full use of their unique property spectrum.

It is anticipated that the fast development of the past years will continue.

References

[1] J. Weissmüller, R. N. Viswanath, D. Kramer, P. Zimmer, R. Würschum and H. Gleiter, Sci., 300, (2003), 312.

[2] C. Park and S. R. Nutts, Mater. Sci. Eng. A, 299, (2001), 68.

[3] T. Ikeda, T. Aoki and H. Nakajima, Met. Mat. Trans, 36A, (2005), 77.

[4] J. Banhart, D. Bellmaan and H. Clemens, Acta. Mate., 49, (2001), 3409.

[5] S. K. Hyun and H. Nakajima, Mat. Let., 57, (2003), 3149.

[6] B. Bauer, S. Kralj and M. Bušić, Tehnički vjesnik 20, 6, (2013), 1095.

[7] J. Banhart, J. Ind. Foundry, 51, (2005), 36.

[8] A. M. Hodeg and D. C. Dunand, Intermetallics, 9, (2001), 581.

[9] W. Deqing and S. Ziyuan, Mater. Sci. Eng. A, 361, (2003), 45.

[10] T. Wada and A. Inoue, Mater. Trans, 44, (2003), 2228.

[11] D. Weaire, Adv. Eng. Mater., 4, (2002), 723.

[12] S. K. Hyun and H. Nakajima, Mater. Sci. Tech., 74, (2004), 667.

[13] J. Banhart, N. A. Fleck and A. Mortensen, Cellular Metals: Manufacture, Properties, Applications, MITVerlag, Berlin, (2003).

[14] H. P. Degischer amd B. Kriszt, Handbook of Cellular Metals, Wiley VCH,Weinheim, (2002).

[15] D. K. Rajak, L. A. Kumaraswamidhas and S. Das, Mater. Sci. Technol., 32, (2016), 13, 1338.

[16] Y. An, S. Yang, E. Zhao and Z. Wang, Mater. Manuf. Processes, 33, 5, (2018), 528.

[17] J. Grabian, Arch. Foundry Eng., 11(1), (2011), 27.

[18] P. Malinowski, J. S. Suchy and J. Jakubski, Arch. Metall. Mater., 58(3), (2013), 965.

[19] K. Gawdzinska, Arch. Metall. Mater., 58(3), (2013), 659.

[20] I. Telejko, H. Adrian and B. Guzik, Arch. Metall. Mater., 58(1), (2013), 83.

[21] J. Szajnar, M. Cholewa, M. Stawarz, T. Wróbel, W. Sebzda, B.Grzesik and M. Stepien, Arch. Foundry Eng., 10(1), (2010), 175.

[22] M. Moradi, Open Access Dissertations, (2011), 481.

[23] Y. Du, A. B. Li, X. X. Zhang, Z. B. Tan, R. Z. Su F. Pu and L. Geng, Mater. Lett., 148, (2015), 79.

[24] S. Sowmiy, P. Nallanukalab, J. Anburaj and B. Simhachalam, Mat. Today, 5 9, 3, (2018), 2036.

[25] J. Jayaraj, B. J. Park, D. H. Kim, W.T. Kim and E. Fleury, Scripta Mater., (2006), 55, 1063.

[26] M. Kolluri, M. Mukherjee, F. García-Moreno, J. Banhart and U. Ramamurty, Acta Mater., (2008), 56, 1114.

[27] L. Zhibin, X. Chen, B. Jiang and F. Lu, Compos. Struct., 145, (2016), 142.

[28] T. Fujita, L. Qian, K. Inoke and M. Chen, in the proceedings of the 16th Int.Microscopy Congress, Sapporo, Japan, 3-8 , (2006), 1864.
[29] K. Gawdzinska and M. Gucma, Arch. Metall. Mater. , (2015), 60, 1.
[30] M. F. Ashby, A. G. Evans, N. A. Fleck, L. J. Gibson, J. W. Hutchinson and H. N. G. Wadley, Metal Foams: A Design Guide, Butterworth-Heinemann, Woburn, MA, (2000).
[31] V. C. Srivastava and K. L. Sahoo, Mater. Sci. - Poland, Vol. 25, No. 3, (2007).
[32] J. Lázaro, E. Solórzano, M. A. Rodríguez Pérez and F. García-Moreno, J. Mater. Sci., 50, 8, (2015), 3149.
[33] C. Girolamo, G. Dodbiba and M. Elisa Tata Procedia Structural Integrity, 2, (2016), 2277.
[34] A. H. Brothers and D. C. Dunand, Mat. Sci. Eng., A,489, (2008), 439.
[35] M. Mahadev, C. G. Sreenivasa and K. M. Shivakumar, IOP Conf. Series: Mater. Sci. Eng., 376, (2018).
[36] A. S. Antenucci, V. Guarino, V. Tagliaferri and N. Ucciardello. Mater. Des., 59, (2014), 124.
[37] Advanced Materials, Metal Foam Market Size & Analysis, Global Industry Report, 2014-2025, Market Research Report, Oct, (2017).
[38] Global Aluminum Foam Market Insights Report, (2019), September.
[39] Al Foam Market: Global Industry Analysis 2013 - 2017 and Opportunity Assessment; 2018 – 2028, Future Marketing Insight, November (2019), REP-GB-8402
[40] Metallic Foam Market: Future Growth and Challenges Analyzed, Market Report, August, (2019).