

Production of Open Cell Foams Out of Aluminium Chips

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Metal foams are type of materials whose properties depend on the structure and size of porosity, so the main task of this research is to examine the effect of porosity and processing parameters of open cell aluminium foams on their properties. In order to achieve the task, experiments were carried out in which quantity and size of space holder material were taken as variables influencing the final quality of metal foams. Sintering was carried on for three of six samples. As a quality indicator compressive strength, energy absorption capability, density, microhardness and electrical conductivity were taken into consideration. Aluminium alloy chips were utilized as a based material for foam production. This way aluminium waste in the form of chips could be recycled without melting process.

Keywords: metal foams, open-cell foam, aluminium waste recycling, solid-state recycling

Introduction

Metal foams are made as imitation of cellular solid structures from nature like wood, sea sponges and bone. The most used materials are aluminium, steel, nickel and titanium (Vikas et al. 2015, García-Moreno 2016). Foams differ by their cell structure, topology and anisotropy, which together with densities have large effect on their mechanical and physical properties. Because of the light weight structure, they have application in automotive industry which lowers the fuel consumption. Purpose of foams is to reduce serious car crashes because of their high energy absorption and long plateau region (Duarte et al. 2018a, Hussain and Suffin 2011, Michailidis et al. 2011). They are also used in airplane and railway construction as well as ship and aerospace industry (García-Moreno 2016). Aluminium foams contain excellent mechanical and chemical properties. They are used because of their remarkable energy, vibration and acoustic absorption (Zhao and Sun 2001). Their corrosion properties are great as well as thermal expansion and although they contain small density, the stiffness of foams remains high. Also, they have an ability to be recycled and that is why foams represent environmental benefit (Hussain and Suffin 2011, Sangeetha et al. 2020).

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Foams can be categorized into open and closed cell structures. Open cell foams have great thermal and electrical conductivity, therefore, can be used for heat exchangers, filters and for medical purposes. The closed cells groups are usually used as high energy absorbers for vehicles, but their cell morphology, i.e., shapes and size of pores, is hard to control which, on the other hand, implicates that mechanical properties cannot be easily controlled (Duarte et al. 2018b). Because of their non-toxicity, open cell foams are used as water purificators. Open cells foams have uniform structure and homogenous pores (Michailidis et al. 2011). They also have greater vibration absorbing capabilities and less compressive and tensile strength than closed ones. Mechanical properties change with the cell size and morphology for both open and closed cell foams (Rajak et al. 2017, Bauer et al. 2013).

Literature Review

Technique which is usually applied for open cell metal foam production, uses metal powder and space holder mixtures due to its advantage over the other techniques. Control of porosity, i.e., pore size and shape, is crucial for obtaining quality foams. One of the most often experimental tests that is conducted for foams is compression test. Three regions can be noticed within stress-strain compression curves. The first part of these curves is linear elastic region and the second is plateau region in which stress oscillates around average stress. The last part is densification region. Compressive properties depend on the cell size. It also increases with the increase of foam relative density (Stanev et al. 2017a). For the production of open cell foams it is needed to remove space holder by leaching, melting or thermal decomposition (Stanev et al. 2017b). As the space holders sodium chloride, carbamide, various carbonates and some polymers can be used (Michailidis et al. 2011). It can also be used magnesium particles and polystyrene as well as saccharose crystals (Papantoniou et al. 2018). The structure of space holder determines the properties like pore size and shape and the percentage of porosity, the production and price of an open cell foam (Stanev et al. 2017b).

Salt (NaCl) can be used as a space holder because of its numerous advantages. It has high melting temperature and fast dissolution in water. It is also free of toxic elements and costs less than other space holders. Its main disadvantage is corrosion of material that occurs when salt is not completely removed. There are a few studies which include aluminium metal foams that are made with salt space holder. Effect of salt morphology on compression properties was studied for foam made by aluminium powder. It was sintered by using argon gas (Michailidis et al. 2011, Stanev et al. 2017b). Foam made with salt has high homogeneity and its porosity varies from 35% to 80%. It is difficult to remove NaCl with porosity less than 35% (Stanev et al. 2017a). Relative density of aluminium foam has lower value than theoretical because of partial dissolution of salt in foam (Zhao and Sun 2001). Mechanical properties and surface of foam pores are tested using distilled water with and without corrosion inhibitors. It is discovered that oxide layer acts as irregular and porous coating and it depends on leaching time. By using an inhibitor

of chromate conversion dissolution, oxide layer had smaller thickness and uniform structure (Stanev et al. 2017a). Foams are made of aluminium powder and particles of NaCl with a sintering dissolution process. By changing the percentage of porosity, the influence of pore morphology on mechanical properties and energy absorption were studied. Higher fraction of NaCl particles, leads to a decrease in compressive strength and increase in energy absorption (Hussain and Suffin 2011). By using super-gravity infiltration open cell metal foams were made with add of NaCl with various particles size (Wang et al. 2018). Aluminium foams with NaCl particles were made with the addition of magnesium for less oxidation. Sintering time, pressure and volume fraction of components were changed to explore their influence on mechanical properties, density and cell morphology (Surace et al. 2009).

As a space holder, carbamide or urea ((NH₂)₂CO) can be also used. Its characteristics are low price, and easy preparation. Influence of urea particles on metal foams was studied by changing the preparation parameters of aluminium foams. Carbamide is prepared with Al₂O₃ and aluminium powder to produce aluminium foam with different porosities (Stanev et al. 2017b). Other study includes open cell foams produced with carbamide percentage in the range from 50 to 80%. It is discovered that size of foam pores depends on the structure of carbamide space holder (Hussain and Suffin 2011). Its main disadvantage is long time of removal from aluminium (Michailidis et al. 2011).

Raw cane sugar was also used as a space holder. It is non-toxic and can be easily removed from the product. Adding Mg and Sn leads to an increase of mechanical properties. By changing the porosity, changes of mechanical properties were studied (Michailidis et al. 2011, Stanev et al. 2017a). Mechanical properties and energy absorption were measured using open cell aluminium foams with silicone rubber and epoxy resin and changing cell size and loading conditions (Duarte et al. 2018b).

Most of the researchers investigated the influence of space holders on metal foams by using metal powders. Only a few of them were using chip waste to produce foams, and all these studies used chip waste to produce closed cell foams. It is interesting to investigate how useful are metal foams, made from recycled materials and what are their mechanical and electrical properties as well as energy absorption. This is a way to make cost savings for foam production. One of the investigations included aluminium closed cell foams that were made using metal powder and TiH₂ as a blowing agent. Mg was also added in the mixture. Oxygen films creation was investigated as well as its influence on foam (Kumar et al. 2013). Other studies were made using foams made with stabilizer Al₂O₃ and TiH₂. The effect of TiH₂ content on pore morphology and mechanical properties were investigated. In this case, aluminium chip waste was used (Tsuda et al. 2006, Kanetake et al. 2008). Aluminium flakes were mixed with saccharose to make foam. Mechanical properties were investigated and great influence on them had sintering temperature (Papantoniou et al. 2018). Another study included aluminium closed cell foams made with CaCO₃ and CaMg(CO₃)₂ as the foaming agents and chips and their processing parameters were investigated (Haesche et al. 2010).

There are no studies about the influence of processing parameters on mechanical properties of open cell foams produced from chip waste. In this work, the influence of space holder size on mechanical and electrical properties, as well as on density and energy absorption of foams were investigated. As a space holders Himalayan salt, urea and table salt were used.

Materials and Methods

Chip waste of aluminium alloy EN AW 2011 whose chemical composition is shown in Table 1, was used in the experiments. Figure 1 shows aluminium chips used as a base material in Al open cell foam production. Chips were obtained from milling process in which cold compressed air was used as a cooling medium, so chips were not contaminated with cooling and lubrication fluid. Chips were obtained out of EN AW 2011 block of dimensions 100 x 100 x 150 mm. All chips had the same volume because they were obtained with the same milling parameters.

Figure 1. Aluminium Alloy EN AW 2021 Chip Waste



Table 1. Chemical Composition of the Aluminium Alloy that Chips Were Made from

Alloy	Si%	Fe%	Cu%	Mn%	Mg%	Bi%	Zn%	Ti%	Pb%	Al%
EN AW 2011	0.1414	0.507	5.6631	0.0225	0.015	0.5603	0.012	0.0059	0.586	rest

As a space holder table salt, Himalayan salt and urea were used with the constant mass fraction fraction of 60%. Table 2 shows dimensions and mass fraction of space holders for all made samples. Average particle size of Himalayan salt is 5.2 mm, for urea is 1.48 mm and for table salt is 4.74 mm. Figure 2 shows different space holders used in the production of open cell foams.

Figure 2. Different Space Holders



Six specimens of open cell aluminium foams were prepared in a cylindrical shape.

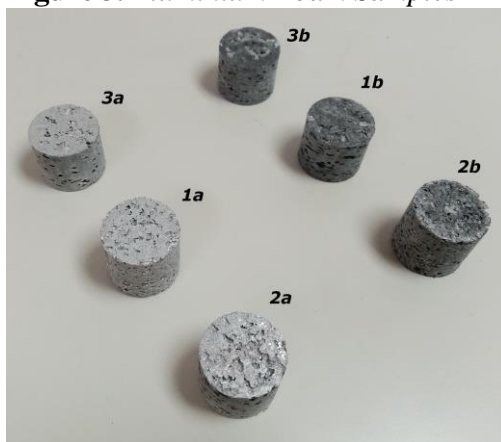
Aluminium chips waste was mixed with space holders in a glass container and rotated in different directions for 5 minutes, so as to achieve uniform distribution of space holders. In order to obtain compacted specimens, mixture was set into a hydraulic press and compressed with force of 500 kN in a mould with a diameter of 38 mm. Force sensor HBM C6A was used for measuring the value of compacting force.

Table 2. Dimensions and Composition of the Obtained Foams

Sample number	Space holder	Mass of sample (g)	Length of sample (mm)	Diameter of sample (mm)	Mass percentage of space holder (%)
1a	Himalayan salt	58.71	34	40.2	60
1b	Himalayan salt	54.04	34.5	40.2	60
2a	Urea	53.22	38.6	40.2	60
2b	Urea	53.25	38	40.2	60
3a	Salt	53.57	34.25	40.2	60
3b	Salt	55.08	34.2	40.2	60

For achieving additional plastic deformation, i.e., to obtain better bonding among aluminium chips mixture was compressed in a mould with a diameter of 40 mm one more time using a force of 500 kN. Pressure sensor HBM P15RVA1/500B was used to measure pressure inside the hydraulic cylinder of the press, and compaction force was calculated using this measurement. After that space holders were taken out of the specimens by leaching in boiling water at the temperature of 100 °C and in duration of half an hour. The final stage of this process is sintering in the nitrogen atmosphere in the furnace Demitem Easy 9 that has maximum operating temperature of 1150 °C. Three of the six samples (1a, 2a, 3a) were sintered at the temperature of 450 °C with holding time fixed to 1 hour. Nitrogen was supplied from an industrial bottle of 50 l. Samples 1a, 2a, 3a were sintered and samples 1b, 2b and 3b were not undergone the sintering process. Figure 3 shows six foam samples made of aluminium chips, after the sintering process of three samples.

Figure 3. Aluminium Foam Samples



Relative density of metal foams was calculated as the ratio of the foam density to aluminium density:

$$\rho_{rel} = \frac{\rho}{\rho_s}, \quad (1)$$

where ρ is density of foam and ρ_s is density of metal from which foam was made (Bekoz and Oktay 2013). Aluminium density amounts 2.7 g/cm^3 .

All specimens were sanded on 600 grit paper. After that, microhardness of foams was measured by Shimadzu micro hardness tester HVM 2T. Microhardness was measured at five different locations on a cross-sectional area of the foams and the average value was calculated afterwards.

Compression test was carried out on all foams using hydraulic press to calculate compressive behaviour of all specimens.

Because of their lightweight structure, foams can absorb energy which is defined as the area under stress-strain curve and was calculated using the following equation:

$$W = \int_0^\varepsilon \sigma d\varepsilon, \quad (2)$$

where W represents capability of the energy absorption, σ compression stress and ε densification strain (Hussain and Suffin 2011). Densification strain in this work was taken as 0.6.

Electrical conductivity of foams can change its values because of wall corrugation, cracks in the cell structure as well as inclusions (Cuevas et al. 2009). It was measured using Agilent 3458A. Resistivity measurement method which was used is four-probe. A direct current passed through the measured specimen and between the first and the last probe. The difference of potential was measured between second and third probe. Resistance range of device was 10Ω . The current had value of 10 mA. Maximum resolution was $10 \mu\Omega$. Electrical resistance $R_f (\Omega)$ of samples 1a, 2a and 3a had been measured before sintering process. Electrical resistance was measured five times for each specimen and average value was calculated afterwards. Electrical conductivity $\sigma (\Omega^{-1} \text{ m}^{-1})$ is reciprocal to electrical resistivity $\rho (\Omega\text{m})$. Electrical resistance can be calculated from the following equation:

$$R_f = \frac{l}{\sigma A}, \quad (3)$$

where l is the length of foam between the second and third probe and A is cross-sectional area of the specimen that is normal to current flow (Dharmasena and Wadley 2002). In this experiment $l=20 \text{ mm}$ and $A=1268,6 \text{ mm}^2$ and electrical conductivity was calculated out of the average electrical resistance.

Results and Discussion

Table 3 shows density, relative density and microhardness for all made samples. From the Table 3, it can be seen that density and relative density are the smallest when urea is used as a space holder, although all foams had the same mass percentage of space holders. Samples with urea have the lowest value of particle size, so the foam pores are smaller than the others. There is no significant difference in densities between foams made of Himalayan salt and table salt because their particle sizes differ by approximately 0.5 mm, while urea is much smaller.

Table 3. *Densities and Microhardness of Six Foams*

Sample number	Density (g/cm ³)	Relative density	Microhardness (HV)
1a	1.234	0.457	33
1b	1.222	0.453	112
2a	1.086	0.402	33
2b	1.104	0.409	111
3a	1.229	0.455	35
3b	1.259	0.466	119

Microhardness of samples without sintering is similar no matter of the kind of space holder, as shown in Table 3. Great difference between sintered and non-sintered samples can be seen. Some authors have investigated that sintering temperatures less than 640 °C result in poor bonding of Al particles, although this study was made for metal powders. The sintering process has large influence on microstructure and mechanical properties of foams (Zhao and Sun 2001). When the samples were cold compressed, because of the plastic deformation, their matrix grains were crushed and that is why microhardness has greater value for aluminium foams made without sintering. When sintered, grains are getting bigger due to the recrystallization process and that leads to smaller values of microhardness. It can be seen that there is no significant difference in microhardness with different densities of aluminium foams under the same conditions.

Energy absorption per unit volume is defined as the area under stress-strain curve which is related to relative density of foams. To have efficient absorption, the foam should deform with small stress oscillation. Difference between foam with large and small absorption properties can be seen in stress-strain diagram. If the foam is brittle, stress oscillations can be seen in the curve, while the one with good absorption properties has smooth curve. Strain hardening can lead to increase plateau stress which occurs when samples are compressed. As relative density is increased, strain hardening increases and densification occurs earlier (Michailidis et al. 2011, Fischer 2016). Absorption capacity has linear increase with the rise of strain until the densification strain. Authors concluded that greater sintering temperature, resulted in higher energy absorption. It is also shown that densification starts earlier by the influence of the radial constrained boundary. Those specimens have larger ability of energy absorption (Papantoniou et al. 2018, Li et al. 2020).

The compressive force was measured using force transducer HBM C6A and displacement of the punch was measured with the inductive displacement transducer HBM WA T-50. Out of the force-displacement measured data engineering stress-

strain curve was calculated. Stress – strain diagram consists of elastic part, plateau stress deformation which has less slope than the elastic part and densification part. Under compression of aluminium foam, at the end of the plateau part, stress increases because of the flattened pores. Walls of pores have brittle cracks. Densification is the last part of diagram area which can be seen in the part with higher slope than the plateau part (Bekoz and Oktay 2013). Density and plateau stress are proportional to space holder size and porosity is inversely proportional to space holder size (Suresh and Vidyashankar 2016). As it can be seen in Figure 4, the sample 2a, which is sintered and made from urea space holder, has the highest stress value. The sample 1b, made of Himalayan salt space holder without sintering has the greatest elastic stress region.

Figure 4. Stress-Strain Curves for Aluminium Metal Foam Samples

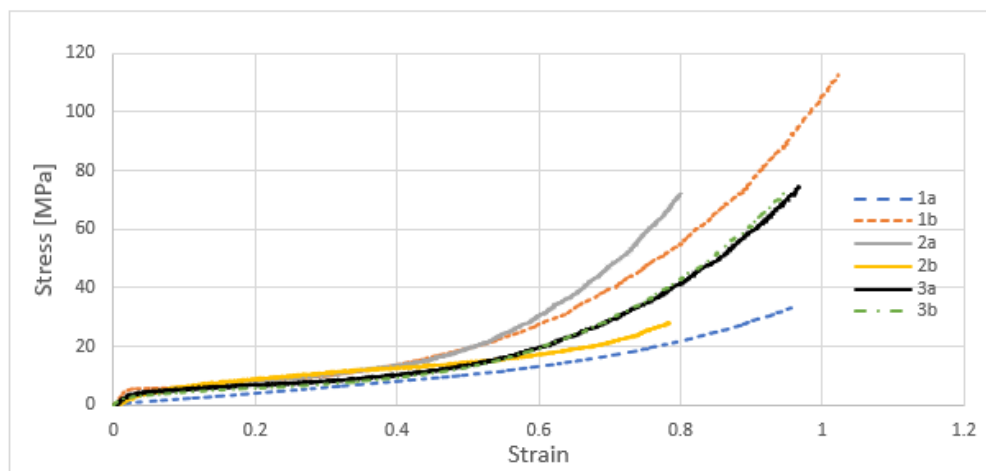


Table 4 shows the properties of produced samples obtained by compression test. As can be seen sintered sample 2a, sample made with urea space holder, achieved the highest compressive strength at strain 0.6. The greatest yield stress occurred for non-sintered sample 1b, sample made with himalayan salt space holder, i.e., space holder with the highest particles size.

Table 4. Compression Properties of Metal Foams

Sample number	Energy absorption (MJ/m ³) at strain 0.6	Yield stress (MPa)	Compressive strength (MPa) at strain 0.6
1a	3.8	1.6	13.2
1b	7.3	5.7	27.7
2a	7.2	3.4	30.8
2b	6.2	3.6	17.3
3a	5.5	3.5	19.6
3b	5.0	2.4	20.2

The highest energy absorption at strain 0.6 of 7.3 MJ/m³ was achieved for non-sintered sample 1b, sample made with Himalayan salt space holder, although sintered sample 2a achieved slightly lower energy absorption of 7.2 MJ/m³. If

sintered and non-sintered samples are compared it can be concluded that sintering process has a sense only for specimens made with urea space holders, because that process leads to high increment of compressive strength and energy absorption capability. Sintering process for samples made with the Himalayan salt space holder does not have sense because that process deteriorates compressive strength and energy absorption capability for these samples. Sintering process for samples made with the table salt space holder also does not pay off, considering that sintering process consumes time and thermal energy and compressive strength and energy absorption capability of these samples do not increase significantly in return. Moreover, compression strength is the same for both sintered and non-sintered samples, while energy absorption slightly increases with sintering.

Figure 5. *Compressive Strength and Energy Absorption to Relative Density Ratio*

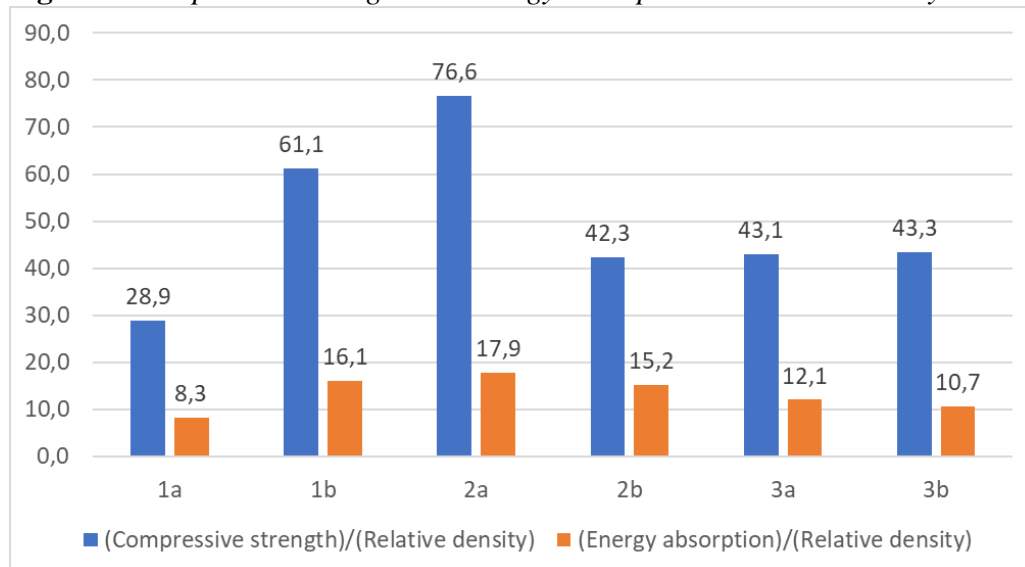


Figure 5 shows compressive strength and energy absorption at strain 0.6 to relative density ratio of obtained foams. It is evident from the Figure 5 that sintered sample 2a made with the urea space holders achieves the highest both compressive strength to relative density ratio as well as energy absorption to relative density ratio. This indicates that foams with smaller particle size of the space holders, in this study urea, are preferable and should be sintered if high compressive strength and energy absorption capability are wanted to be obtained. Explanation for this result seems to be higher shear plastic deformation obtained in cold compaction procedure, due to smaller size of the space holders, and higher shear plastic deformation assures better braking of the aluminium oxide on the chips surface what in turn results in direct aluminium to aluminium contact and better chips bonding. Sintering support this bonding process even more due to improvement in diffusion process at higher temperatures. Also foams with smaller space holder particles exhibit thicker walls and struts among the foam cells. Figure 5 also shows that non-sintered foam made with Himalayan salt space holders exhibits rather high compressive strength and energy absorption to relative density ratio which indicates these foams could be considered as an alternative to sintered foams made with urea. This is especially

pronounced when production costs are taken into consideration because this foam does not need sintering process which consumes thermal energy. The worst compression properties exhibit sintered foam made with Himalayan salt space holders. The reason for this seems to be thinner struts and walls of the cells, and worse aluminium to aluminium contacts due to poorer breaking of the aluminium oxides. This is even more pronounced when foam is heated during the sintering process because aluminium oxides inhibit the diffusion process.

Table 5. Values of Electrical Resistance and Conductivity of Metal Foams

Sample number	Average electrical resistance ($\mu\Omega$)	Electrical conductivity ($\Omega^{-1} * m^{-1}$)
1a	416	$3.7785 * 10^4$
2a	2350	$6.705 * 10^3$
3a	982	$1.6006 * 10^4$

In the previous investigation of other authors, it was concluded that size of pores affects the conductivity. It has been proven that with the same porosity, the smaller size of space holders leads to a lower conductivity. This happens because more air is trapped, and small size leads to greater interfacial area, what implicates that more area is covered with aluminium oxides, which is an electric insulator. When larger size of space holder particles are used, structure is more bonded, but its thin wall of cells can lead to increase of conductivity (Cuevas et al. 2009, Goodall et al. 2006). It can be seen that the greatest electrical conductivity had the sample 1a made with Himalayan salt as a space holder, i.e., space holder with the largest particles size. As the size of space holder is getting smaller, the electrical resistance of samples increases. Table 5 shows the average value of electrical resistance calculated after five measurements and electrical conductivity of the foams calculated out of average electrical resistance using the equation (3).

Conclusion

The relative density of aluminium foam is the smallest when using the urea as a space holder. There is no significant difference in density and relative density between table salt and Himalayan salt. Density has no influence on microhardness of the samples. There is a great difference between microhardness values of sintered and non-sintered samples. It has been shown that sintering leads to an increase in grain size, which results in significant fall in microhardness.

Sintered foams made with the urea space holders have achieved the highest both compressive strength to relative density ratio and energy absorption to relative density ratio. The worst compression properties exhibit sintered foam made with Himalayan salt space holders. Non-sintered foam made with Himalayan salt space holders exhibits rather high compressive strength and energy absorption to relative density ratio which indicates these foams could be considered as an alternative to sintered foams made with urea.

One of the most influencing factors on electrical conductivity is the particle size of space holders. It has been shown that urea, which had the smallest size of

particles, resulted in the largest electrical resistance which in turn led to the smallest electrical conductivity values.

It is obvious that compressive strength and energy absorption with regard to electrical conductivity are opposing properties, meaning that smaller space holder increases compressive strength and energy absorption while on the other hand decreases electrical conductivity. In that context optimization of the processing foams parameters is needed.

Obtained metallic foams, due to their light weight and energy absorption properties, can be successfully applied as crash absorbers in the automotive industry, especially for electrical vehicles where operation range is still critical. Another application in the context of energy absorption capability is military vehicles protection and mitigation of high energy impacts. These foams have large surface area and good thermal and electrical conductivity which makes them ideal for heat dissipation devices, electrodes in batteries or electro-chemical purposes.

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