On the Way to Real Applications: Aluminum Matrix Syntactic Foams

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Abstract

In recent times, aluminum matrix syntactic foams (AMSFs) have become considerably attractive for many industries such as automotive, aviation, aerospace and composite sector due to their features of low density, good compression strength, perfect energy absorption capacity and good ductility. Since the AMSF includes filler materials providing high porosity, it can be also named as composite foam and can be placed between traditional metal foams and particle reinforced composites. Glass and ceramic hollow spheres, fly ash cenospheres and ceramic porous materials are usually used in the AMSFs, but, lately, different types of fillers being cheaper and stronger have also being investigated. Although many scientific efforts have been made for the last decade to understand mechanical and physical properties of these advanced materials, studies have mainly been performed on relatively small size samples and remained in laboratory. Therefore, there is still room for improvement in terms of fabrication techniques. In this paper, our aims are to scrutinize newest studies about ASMFs, to create new viewpoints and to introduce an alternative bright perspective for probable real applications.

Keywords: aluminum alloys, syntactic foam, microstructure, compression response, fracture mechanism

1. INTRODUCTION

Syntactic foam is an advanced engineering material composing of hollow or porous ceramic particles and a polymer or metal matrix. Even though polymer matrix syntactic foams (PMSFs) have become commercial for some time, metal matrix syntactic foams (MMSFs) have not been investigated in detail and have been fabricated only in laboratory scale till the recent years. Fig. 1 given below demonstrates some syntactic foam samples produced with casting methods.

Figure 1. Some examples of MMSF and PMSF materials [1]

Compared to other MMSFs, nowadays, AMSFs have been notably popular due to their unique properties like low density, good strength under compressive loadings, perfect energy absorption capacity and noteworthy ductility. They can be either considered as particle reinforced composites or can be interpreted as closed cell metal foams by reason of their original inner structure [2]. The synergetic effect between Al matrix and filler particle plays an important role both for mechanical and physical features.

As matrix materials, commercially pure (cp-Al), A356, A380, 2014, 6061 and 7075 series are frequently used while the reinforcement is usually fabricated from ceramics comprising of some kinds of oxides or from natural sources (porous rocks and stones) and metals [3-5]. It is clear from the technical literature that spherical hollow Al_2O_3, SiC, SiO_2 ceramics and fly ash cenospheres are common reinforcement materials [6-8]. Although these thin walled ceramic hollow spheres display good physical and mechanical performance, owing to their manufacturing process they can be counted relatively expensive. However, recently, natural based porous fillers have been started to be used by researchers being interested in Al foams. Pumice, which is a porous rock being formed as a result of volcanic eruptions, and expanded perlite (cousin of pumice) are good examples for this situation. Thanks to these natural fillers, desired mechanical features also could be reached with low production cost [5], [9].

It is obvious that total porosity of the foam is majorly controlled by fillers own porosity [10]. In addition to this, certain shrinkage cavities forming between matrix and filler interfaces or in matrix itself can lead to porosity increment [11]. Density and total porosity of the filler are also decisive for final foam density. In some cases, filler materials tend to combining or they leak into the hollow spheres from surface cracks and defects, which results in unwanted high density foam [12].

Low melting point, availability of heat treatment (2XXX, 6XXX and 7XXX series) and relatively low density are main advantageous properties of Al alloys [13]. Application potential of AMSFs is more promising in the automotive than the other sectors since it is a perfect candidate to provide some key requirements such as lightweight construction, energy absorption and damping insulation (i.e. crash boxes between impact beam and the front rail) [14]. Aside from improving engine technologies, total weight decrease is also very critical for the fuel efficiency and maintenance costs. Herein, AMSF parts can provide these requirements without any setbacks.

In this paper, fabrication methods, macroscopic/microscopic features and physical/mechanical properties of AMSFs were reviewed in detail in the light of past and recent literature efforts. Apart from well known traditional fillers, some new alternative fillers tried in the latest works were also stated. In addition, some probable future applications of these advance engineering foams were emphasized depending upon target industrial areas in order to provide broad perspective for the next studies about AMSFs.

## 2. FABRICATION AND PHYSICAL/MECHANICAL PROPERTIES

2.1. Fabrication Methods

Infiltration casting and dispersion technique are two main methods for manufacturing of the AMSFs and both of them consist of unlike sub methods shown in Table 1. All fabrication methods have some advantages and handicaps with regards of uniform distribution of fillers, casting defects (voids, pits and cavities), dimensional accuracy, surface quality and cost effectiveness.

Table 1. Fabrication Methods of AMSF

Fabrication Methods	
Infiltration Casting	Dispersion Casting
- Pressure infiltration	- Stir casting
- Counter gravity	- Centrifugal
- Gas pressure	- Buoyancy method
- Vacuum assisted	
- High pressure	

Infiltration casting methods are often applied in different ways to produce AMSFs and other alternatives have still been investigated to improve physical and mechanical features. Many researchers have utilized infiltration casting methods to obtain uniform foam structure. Based on manufacturing method, process parameters shown in Fig. 2 might

change.
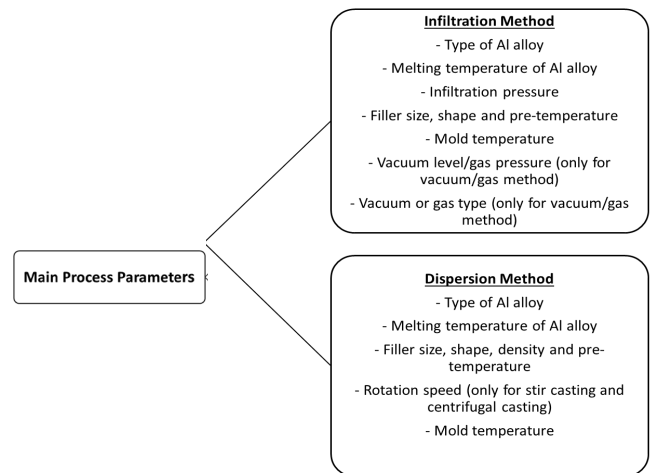
Figure 2. Main process parameters of AMSF fabrication

Pressure infiltration is a very common and preferable method in comparison with the other ways and it works with the principle of gravity assisted infiltration. Usually, preheated filler materials are placed into the bottom section of the die and molten Al alloy is poured on them before the main pressure. In a work performed by Zhang et al., cp-Al/fly ash cenosphere syntactic foam was manufactured with pressure infiltration under a pressure of 0.8 MPa. At first, they sintered the cenospheres in a steel mold at 650°C to get preform. Then, an Al block was placed into the same mold for melting and finally infiltration pressure was applied with a ram [15]. Concordantly, Zhang et al. used Al-Mg alloy 5A06 (Mg 6 wt.%) and glass cenospheres as matrix and filler materials while Tao et al. studied on Al 6082 alloy/porous 75-500 μm ceramic foam in another efforts by applying the same casting technique mentioned above [10], [16]. Zhao et al. tried a similar method for fabrication of cp-Al/porous 0,25-4 mm ceramic foam with 20 mm diameter and 30 mm height. They used four different fillers that were free before the infiltration pressure of 4 MPa [17]. Apart from these works, Weise et al. focused on another method that can be called high pressure infiltration because of the pressure interval of 5-20 MPa and the research group produced A380/S60HS hollow microsphere foams at 730°C in the pre heated (295°C) sleeve whose forward tip was sealed [18].

As an alternative method, counter gravity infiltration (backward) can be considered and it is used in some investigations by researchers. In this method, contrary to the standard gravity assisted method, matrix material is filtered between fillers against the gravitational force. In this technique, die design is highly important due to the control of the part dimensions (usually specially designed die design is required).Taherishargh et al. fabricated A356/expanded perlite(3-4 mm) syntactic foam with this principle. Firstly, a block of Al was placed in graphite crucible and a graphite mold filled with perlite particles was put on the A356 block. Then, the assembly was closed with stainless steel chamber and whole system was delivered to electrical furnace. At 720°C, the assembly was removed from the furnace and finally, the graphite mold was pushed downwards by

forcing the molten matrix into the mold for infiltration [19]. Besides, the same group produced A356/pumice(2-4 mm) syntactic foam having 27 mm diameter and 41 mm height with the same backward infiltration method [5].

In order to Al filtration, vacuum can be counted as a good solution and it has been applied by many investigators for years. Thanks to the applied vacuum, more infiltration flexibility can be provided for liquid Al matrix and even narrow gaps can be filled with the metal. Palmer et al. fabricated Al 1350, 5083 and 6061 syntactic foams by means of vacuum assisted infiltration. Fillers utilized in the study were ceramic microspheres (45 and 270 µm diameters). If it is glanced at the method briefly, an alumina crucible was filled with the microspheres. When solid matrix block on the fillers melted, pressure of 450 kPa was applied to provide downward infiltration [20]. Orbulov et al. benefited from Ar gas for infiltration of melted AlSi12 and Al99,5 alloys between 100-150 µm micro balloons and optimized infiltration temperature, time and pressure [21]. Dunand et al. designed custom built Ar gas pressure system to manufacture cp-Al and Al 7075 matrix syntactics. A mixture of 45 vol.% crystalline mullite $(3Al_2O_3-2SiO_2)$ and 55 vol.% amorphous silica (SiO_2) microspheres with 15-75 µm was packed in graphite crucible, then a block Al alloy was placed above the microspheres. The system was heated under vacuum to melt the block at 720°C and 3,5 MPa pressure of Ar gas was introduced to the system in order to force molten alloy into empty spaces between microspheres [22]. Schultz et al. also worked on Al-A206/SiC foams by implementing vacuum assisted infiltration and they found that 0.5 bar Ar gas pressure was enough for fully infiltration between 1 mm fillers at 750°C [23].

As for filler conditions, it can be said that there are two options for filler materials before the infiltration process: preform shape with sintering or free mixture without pre sintering. In the first option, the fillers are in physical contact despite the fact that in the second option the fillers are separated from each other by Al matrix. As a result of this situation, the mechanical responses will not be alike. Preform shape filler materials can transmit deformation cracks to one another so that crack propagation takes place easily. On the contrary, cracks are stopped by Al matrix in the foams fabricated with free mixed fillers.

Aside from the infiltration techniques, there are some different methods in which dispersion mechanism is worked fundamentally. Stir casting is one of these dispersive techniques that uses basically a mechanical stirring equipment and liquid Al chamber. The process is based on classic blending and is carried out at elevated temperatures. For example, Sahu et al. fabricated Al 2014/cenosphere syntactic with stir casting. At the beginning, fillers with 100 µm diameter were preheated at 1000-1100°C and Al alloy was melted, then, before transferring to the preheated forming die, fillers were added into the molten alloy pool for stirring at 600-800 rpm for 5-10 min [24]. In another study, when they examined dry sliding wear behavior of Al LM13/100-200 µm cenosphere syntactic foam, Mondal et al. availed stir casting method. At 670°C, LM13 was melted, mixed preheated fillers at 900°C were added into the molten alloy, mechanical stirring at 250-300 rpm for 15 min were carried out and the mixture was transferred to solidification die [25]. Mondal et al. also manufactured AlSi12Cu1Mg1/cenosphere(100-200 µm) hybrid foams with different densities by means of CaH_2 foaming agent [26]. Furthermore, in surveys carried out by Daoud et al., researchers proved that other kinds of MMSFs like Mg and Zn/fly ash cenosphere(150 µm) foams could be manufactured with stir casting by optimizing process parameters [27], [28].

Centrifugal casting is another dispersion technique by which AMSF can be fabricated by means of centrifugal force. This technique can be applied both for closed packed and loosely

Table 2. Casting Methods of the AMSF

Technique	Advantages	Handicaps	Key Instructions
Pressure Infiltration	Simple application and mold design	Difficult for small size fillers	Pre-heating of the mold and fillers
	Good wetting of fillers	Difficult for complex shapes	Avoiding from matrix/filler reaction
	Homogenous foam structure		Lubrication of the mold walls
Counter gravity infiltration	Uniform filler distribution	Not useful for micron level fillers	Optimizing of male/female mold temperature
	No requirement for expensive apparatus	Difficult for complex shapes	True selection of mesh apparatus
	Good wetting of fillers		Optimizing of filtration pressure
High pressure die casting	Highly suitable for automation	Expensive for small quantity fabrication	Lubrication of sprue and mold walls
	More promising for complex geometries	Extra design parameter (piston speed)	Finding of system regime duration
	Controllable, rapid and repeatable		Correct mold inlet design
Gas/Vacuum Infiltration	Good filtration from narrow gaps	Need for additional tanks and pumps	Optimizing of vacuum level
	Proper for micron size fillers	Relatively expensive than pressure infiltration	Right determination of gas pressure
	Uniform foam structure		Pre-heating of the mold and fillers
Stir casting	Easy handling	Not easy out of furnace	Adjusting of mixer rotation speed
	Effective matrix/filler mixing	Requirement of secondary treatments	Avoiding from jellying
	Simple fabrication components		Correct mixing time
Centrifugal casting	Homogenous circular foam structure	Limited with circular geometry	Determination of optimum rotation speed
	Controllable setup		Designation of casting temperature
Buoyancy technique	Very simple application	Useless for high density reinforcements	Ensuring density range of fillers
	Low cost equipment and control	Not useful for bigger and sophisticated forms	Avoiding from filler/matrix reaction

aligned filler particles. When Ferreira et al. worked on corrosion behavior of A356/SiO$_2$-Al$_2$O$_3$ hollow micro balloon syntactic foams, they used centrifugal casting for sample production. At 630°C, inside a resistance furnace, Al alloy and hollow fillers were mixed mechanically under protective N$_2$ atmosphere. After the mixing, system temperature was escalated 850°C for casting with 750 rpm rotational speed [29]. In some cases, because filler density is lower than that of the molten metal and they are not packed closely, heterogeneous volume distribution of the fillers can be beheld from the rotation axis to mold end [3]. Buoyancy technique is a simple dispersion strategy and it can also be utilized for fabrication of syntactics. Basically, thanks to density difference, low density filler particles prone to floating on the molten matrix and take form in the die. Kim et al. fabricated epoxy/glass hollow microsphere syntactic foams of various densities via buoyancy method [30]. Table 2 shows the all production methods along with their virtues and handicaps in detail.

2.2. Macro and Micro Properties

AMSFs are hollow or porous particle filled composites and can be considered as advanced engineering materials. General interest for these foams has been rising lately owing to their low density within a close range (1 – 2.2 g/cm³). Table

Table 3. AMSF densities obtained with unlike foam components

Study	Matrix	Filler Type	Filler Size	Density (g/cm³)
Zhao, 2009 [10]	Al 6082	Ceramic (SiO$_2$-Al$_2$O$_3$)	75-125 µm	1,14 - 1,41
Gupta, 2013 [8]	A356	SiC	1 mm	1,81
Gupta, 2015 [12]	A356	Alumina	3 mm	1,62 - 2,11
Mondal, 2017 [25]	LM13	Cenosphere	100 - 212 µm	1,9 – 2
Taherishargh, 2014 [19]	A356	Expanded perlite	3 - 4 mm	1,05 - 1,13
Dou, 2007 [7]	Pure Al	Cenosphere	90 - 150 µm	1,43 - 1,52
Gupta, 2006 [31]	A356	Cenosphere	45 - 250 µm	1,25
Zhao, 2007 [17]	Pure Al	Glass sphere	0,5 - 4 mm	1,58 - 1,88
Orbulov, 2013 [32]	AlSi12	Ceramic (SiO$_2$-Al$_2$O$_3$-Mullite)	150 µm	1,35
Castro, 2013 [33]	Al 2024	Alumina	3 - 4,25 mm	1,25
Zhao, 2019 [34]	Al 6082	Ceramic (SiO$_2$-Al$_2$O$_3$)	75 - 500 µm	1,40 - 2,29
Puga, 2018 [35]	AlSi7Mg	Expanded clay	2 - 7,5 mm	1,27 - 1,45
Goel, 2019 [36]	Al 2014	Cenosphere	75 - 150 µm	1,85 - 1,88
Orbulov, 2015 [37]	AlCu5	Ceramic (SiO$_2$-Al$_2$O$_3$-Mullite)	1,45 mm	1,84
Zhang, 2016 [38]	Pure Al	Cenosphere	80 – 160 µm	1,43 - 1,52
Fiedler, 2018 [39]	A356	Expanded perlite	3 - 4 mm	1,06 - 1,11
Mondal, 2009 [40]	Al 2014	Cenosphere	84 µm	1,5 - 1,9
Taherishargh, 2015 [5]	A356	Pumice	2,8 - 4 mm	1,48 - 1,5
Zhang, 2016 [16]	5A06	Cenosphere	15 - 75 µm	1,17 - 1,32
Schultz, 2013 [23]	A206	SiC	1 mm	1,87 - 1,95
Szlancsik, 2018 [41]	A356	Expanded perlite	3 - 4 mm	0,7 - 1.1
Kadar, 2019 [42]	Pure Al	Expanded perlite	1 - 2 mm	1,1
Mondal, 2018 [46]	Al 2014	Alumina	1 mm	1,72 – 2,27

3 shows density values of some AMSFs fabricated with different techniques and particle sizes. Filler materials, for instance; alumina/glass spheres, fly-ash cenospheres, carbide spheres, expanded ceramic spheres and other porous rock particles, are majorly responsible for density diminishment and they also control total porosity ratio of the foam [10], [18].

Fly ash cenospheres are commonly preferred by investigators because of their cheapness and easy attainability. Indeed, ashes created from thermal power plants are recycled as cenosphere particles and thanks to benefication process, low density flawless cenospheres can be sorted out for production [11]. Although they are more expensive than other porous alternatives like expanded glass, perlite and pumice, hollow spheres of Al$_2$O$_3$, SiC, and SiO$_2$ have high porosity due to their very thin outer shell. Engineered hollow spheres usually perform better than fly ash cenospheres in terms of compressive behavior, however, according to some studies, natural based cellular particles (i.e. expanded glass and pumice) can be considered as promising alternatives [5], [19]. From milimeter to micrometers, all reinforcements have to possess non-damaged and smooth outer surface, otherwise molten matrix may leak into the fillers, which triggers density rise. Low wettability of the fillers may cause casting cavities around matrix-filler interfaces, which affects mechanical responses in a noteworthy manner.

During the fabrication, enough wettability of the filler particles is highly important that determines envelopment quality of the fillers by Al matrix. Filler roundness effects wettability in a positive manner, but some investigations also shows that complex porous fillers can be used effectively with a good wettability [19], [39], [41]. In Fig. 3, two types of the AMSF (Al 7075/hollow alumina with 1,7 g/cm³ density and Al 7075/porous pumice with 1,5 g/cm³ density) having perfect reinforcement/matrix harmony are demonstrated in detail.

A wide range of Al alloys have been used in diversified industries for a long time and they basically are divided into two groups: heat treatable and work hardened alloys [13], [43]. Cp-Al, A356, A380, 2014, 6061 and 7075 series are frequently preferred matrices for AMSFs since some of them are suitable for infiltration with good viscosity and the others are heat treatable after the fabrication. Depending on filler/matrix combination and fabrication conditions, certain chemical reactions written below may occur between matrix and filler, especially particle with high SiO$_2$ [44].

$$4Al_{(l)} + 3SiO_{2(s)} = 3Si_{(s)} + 2Al_2O_{3(s)} \quad (700 - 850°C) \quad (1)$$

In this chemical activity, amorphous SiO$_2$ in the filler composition can transform to crystalline Al$_2$O$_3$ which leads to zonal stiffness increment at the matrix/filler interfaces. Besides, syntactic foam density may go up due to probability of filler wall declination and total porosity of the foam may diminish. By avoiding high melting temperature and applying rapid solidification that kinds of adverse effects of this

reaction can be minimized or completely blocked.

Characteristic microstructure of the AMSF can be seen in Fig. 4 with combination of both theoretical and a few real images.

Al alloy and filler materials with huge close gaps or porosity compose main part of the microstructure, however, based on matrix/filler match and process variables, some fillers may exhibit combining tendency or may cracked from outer walls [17], [31], [45]. This situation results in molten matrix leakage into inner gaps of the fillers and can dominate fracture style of the foam. Moreover, during solidification stage, by reason of different thermal conductivity of the filler and matrix alloys small casting voids or shrinkage cavities can be beheld around matrix/filler interface [11], [31].

Aforementioned micro properties are typical for AMSFs and considerably decisive on the mechanical behaviors by altering deformation/fracture style. Then, if the other kinds of MMSFs like Fe, Mg or Zn matrix foams are examined, similar microstructures with AMSFs can be detected easily

[47-52]. Aside from fabrication conditions and matrix/filler features, heat treatment of Al matrix should also be taken into consideration from the point of microstructure of the AMSF which directly affects matrix phase formation [53-55].

2.3. Mechanical Properties

AMSF can be described as an advance particle reinforced composite owing to its physical formation, but, at the same time, it has close cell foam structure by way of added hollow/porous reinforcements. Filler materials play an important role on the mechanical features of the AMSF as they provide almost all of the foam porosity. Type of the Al alloy, chemical composition of the filler, pore condition of the particles (hollow or porous), size range of the filler, fabrication style, process parameters and heat treatment are other effective variables determining the mechanical responses. AMSFs are designed to be utilized under compressive loadings and existing efforts in the literature usually focus on their low (quasi-static) and high speed compression properties. In
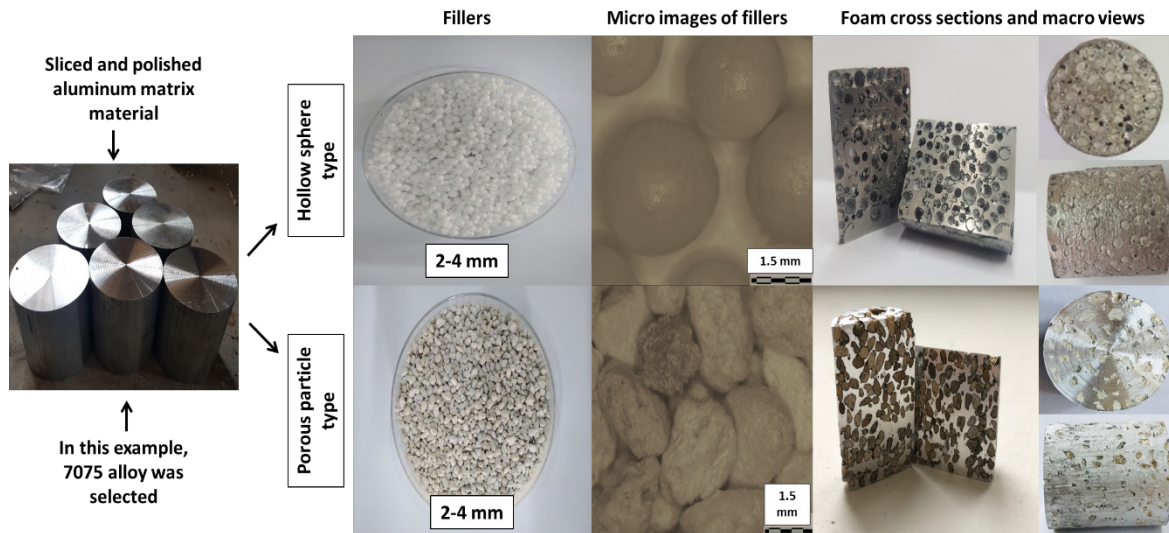

Figure 3. Physical analysis of different Al 7075 syntactic foams
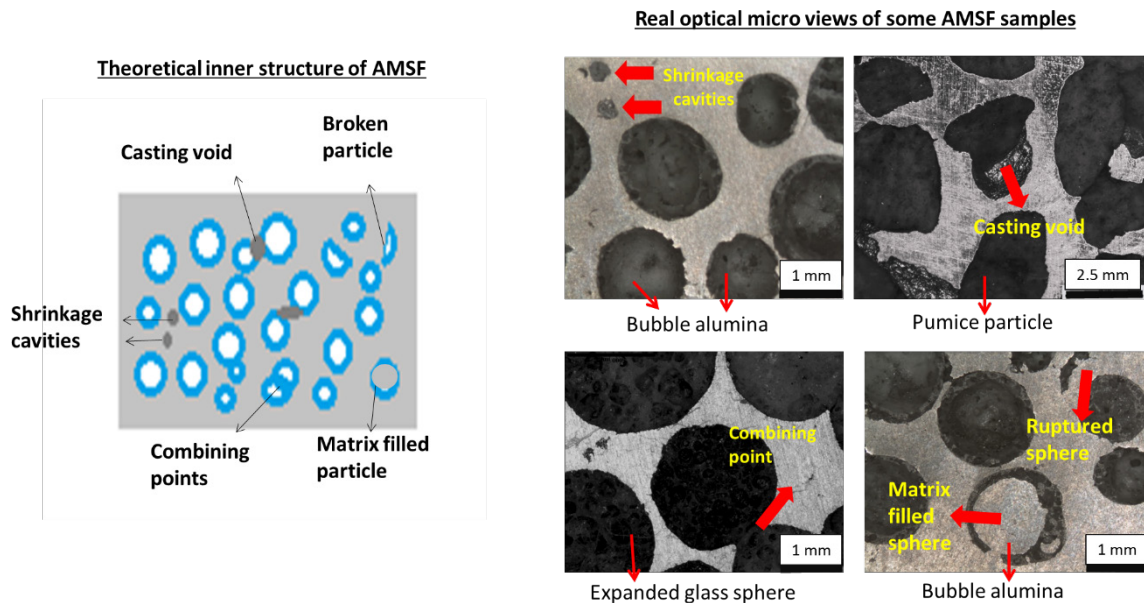

Figure 4. Characteristic microstructure of the AMSFs

order to correct interpretation of the features, ISO 13314 standard is availed by researchers [56]. Since filler particles are engineered ceramics or hard natural rock fragments with high modulus and stiffness, compressive load is largely carried by these elements during the deformation. Fig. 5 shows an example for determination of mechanical features according to ISO 13314. The slope of the linear area is the quasi-elastic gradient (QEG) and 1% offset yield stress is accepted as compression strength (σ_{com}). Plateau stress (σ_{plt}) is the arithmetic mean of the stress values between 20% and 40% strain. Also, densification strain (ε_{den}) is corresponding strain for 1,3 times plateau stress and W is the absorbed energy that is calculated from area under the stress/strain curve up to %50 strain.
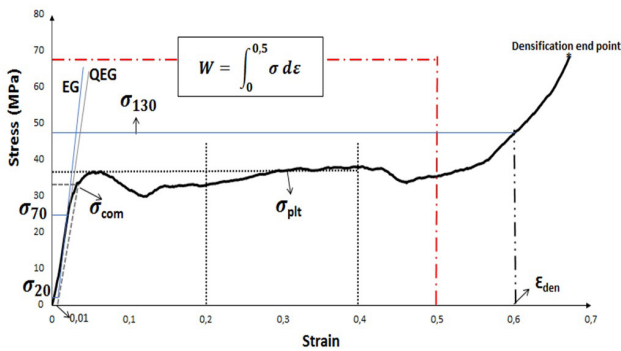

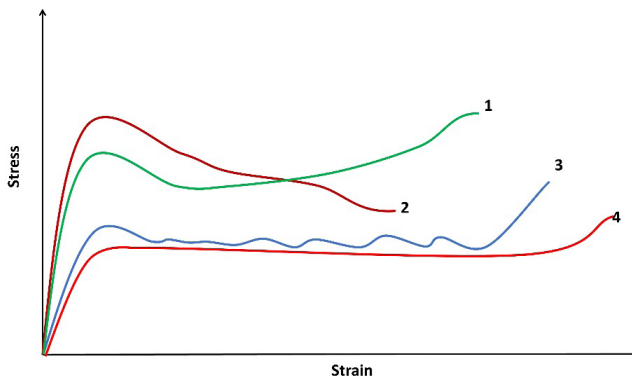**Figure 5.** Interpretation of ISO 13314 standard

Figure 6. Probable stress/strain graphs for AMSF

After the mechanical observations, researchers emphasize that different kinds of stress/strain curves imaged in Fig. 6 might occur depending upon filler pore structure and Al alloy type. For instance, due to strain hardening and heat treatment, curve 1 has an increasing plateau trend although curve 2 exhibits declining trend. Curve 3 represents Al syntactic filled with porous/cellular reinforcement and curve 4 belongs to ideal theoretical behavior with perfect plateau region. Table 4 points main mechanical features of some AMSFs fabricated in earlier studies in terms of loading conditions. Usually, there are two principle deformation styles for AMSFs based on filler structure and strength of Al alloy [22], [57]. If the flow strength of Al alloy is lower than filler crush strength, type 1 deformation depicted in Fig. 7 is seen. Characteristic features of this kind of deformation are barreling effect and good elongation till the densification. Conversely, if the flow strength of matrix alloy is higher than

filler crush strength, type 2 deformation is beheld. Usually, after the type 1 deformation, foam samples remain majorly monolithic and only small fragments break out from the main composite body. However, as for the type 2, typically, 45° shear bands and major deep cracks with low elongation are clear evidences and foam samples often divide into two or more discrete sections.

Table 4. Literature data for the mechanical features of AMSFs

| Study	Deformation type	Foam Components	σ_{com} (MPa)	σ_{plt} (MPa)	ε_{den}
Gupta [8]	Quasi-static	A356/SiC	181	126	0,45
Gupta [8]	Dynamic	A356/SiC	130	*	*
Zhao [10]	Quasi-static	Al 6082/ SiO_2-Al_2O_3	53,3	63,7	0,43
Gupta [12]	Quasi-static	A356/Al_2O_3	106,5	62,8	0,6
Gupta [12]	Dynamic	A356/Al_2O_3	164	*	*
Taherishargh [5]	Quasi-static	A356/Pumice	47	65	0,45
Orbulov [57]	Quasi-static	Al99,5/Globocer	50	51	*
Orbulov [57]	Quasi-static	AlSi12/Globocer	114	57	*
Wu [58]	Quasi-static	Al 6061/Cenosphere	45	40,5	0,5
Wu [58]	Dynamic	Al 6061/Cenosphere	55	*	*
Schultz [59]	Dynamic	A380/Al_2O_3	120	*	*
Taherishargh [19]	Quasi-static	A356/Expanded perlite	37,2	44,7	0,59
Zhao [17]	Quasi-static	cp-Al/SiO_2-Al_2O_3	*	41,7	0,3
Weise [18]	Quasi-static	AlSi9Cu3/Glass bubble	190	180	0,45
Zhang [38]	Quasi-static	cp-Al/Cenosphere	64,7	60,8	0,37
Zhang [38]	Dynamic	cp-Al/Cenosphere	106,5	*	*
Hao [60]	Quasi-static	ZL111/Al_2O_3	61,8	56,4	0,44
Hao [60]	Quasi-static	cp-Al/Al_2O_3	61,5	46,5	0,46
Akinwekomi [61]	Quasi-static	cp-Al/Cenosphere	38,6	26,8	0,6
Goel [36]	Dynamic	Al 2014/Cenosphere	572	*	0,4
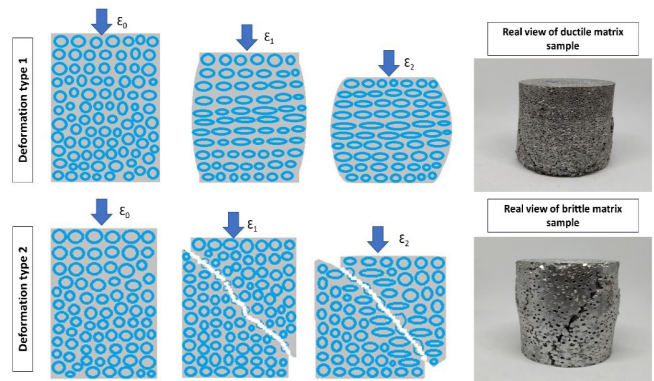
Figure 7. Main failure mechanisms of AMSF samples under compression

Aside from compressive properties, recently, some researchers focus on other loading types like fatigue and notch sensitivity [41], [62- 64]. Orbulov et al. worked on fatigue behavior of different AMSFs and they claimed that matrix ductility and filler diameter strongly affected the fatigue response [65]. Guan et al. measured impact response of Al 7075/ceramic foam by performing drop weight test and stated that Al and big size fillers combination exhibited better results [66]. In the light of these valuable efforts, it is highly possible that many other modes of loadings such as fatigue, creep, low temperature loading and bending will be investi-

gated for AMSF in the upcoming years.

3. POSSIBLE FUTURE APPLICATIONS

High porosity engineering metals are typically classified as conventional metal foams (Al, Mg, Ti metal foams etc.) and syntactic foams (metal + ceramic filler). Owing to their unique properties, traditional Al foams and Al matrix syntactic foams are designated for similar application purposes like high specific weight, high stiffness, perfect compression strength, good damping isolation, high energy absorption capacity, vibration isolation and fine acoustic features [2], [67- 68]. In today's competitive industrial world, from automotive and aviation to aerospace and construction, many sectors endeavor to drop manufacturing cost without sacrificing quality, so advanced engineering materials such as composites, foams and syntactic foams have become more attractive for many companies [2],[11],[14], [69-73]. Standard Al foams have pores stemming from some gases which reduce weight [68], [74-76], but it may cause some handicaps like difficulties in controlling the size and shape of the pores. AMSFs have big potential for real applications because they are not only lighter than traditional particle reinforced Al composites but they also response better than conventional Al foams in mechanical loadings due to their uniform size/shape distribution.

Along with the increasing awareness of environmental pollution and solid rules on total gas emission, the automotive industry is striving to solve total weight and fuel efficiency problems. In this context, it is true to say that AMSFs, which can be used as pillars, crash boxes or other structural components in a car, can fulfill mechanical requirements illustrated in Fig. 8 as well as total weight reduction.

Likewise automotive, aerospace and aviation industries also attach importance to fuel efficiency, lightweight vehicle construction and perfect mechanical properties. For instance, in the 1970s, Concorde airplanes were built solely with %7 fiber reinforced composites [77], but today, according to Giurgiutiu [78], Boeing 737 aircraft is widely composed of lightweight composite materials (%80 by volume). In a similar vein, another aircraft-maker Airbus also prefers advanced composite materials for aircraft fuselage parts and wing structures [79]. AMSFs, particularly as single body parts in the wings and core material for sandwich composites in the fuselage, may be an alternative to traditional composites in aircrafts and other air vehicles. They are notably lighter than fiber reinforced composites and can absorb more energy during deformation in case of undesired plane crashes. Aircraft wings are produced with specific types of Al alloys offering a combination of lightness and strength comparable to other kinds of metals. Herein, as a consequence of AMSF investigations, it can be alleged that this advanced foam might be an even better material and more appealing from the points of safety and fuel efficiency by the reason of its unique low density and plateau behavior.

Even though different casting techniques are applied for AMSF fabrication, in order to manufacture complex shapes and bigger geometries, we consider that some advanced casting techniques or secondary machining are strongly needed for real applications. Lately, researchers worked on machining of Al matrix composites to obtain complex final shapes via certain advanced manufacturing methods like abrasive water-jet cutting/turning, electrical discharge machining, laser cutting and ultrasonic machining [80-87]. On account of its perfect cutting/turning quality and availability for wide range of materials, abrasive water-jet system can be considered for final shaping of AMSF in the next years. Compared to other methods, water-jet systems provides better surface quality and dimensional accuracy without any thermal effects in the microstructure that may emerges in laser machining. Furthermore, regardless of filler type, by optimizing the process parameters of stand-off distance, traverse speed, water pressure, impact angle, abrasive type and size, all versions of AMSFs can be cut and turned with water-jet.

Apart from its outstanding mechanical properties, AMSF has also a potential of sound insulation as well as low thermal conduction owing to its high porosity. Therefore, there is no inconvenience to assert that thanks to these characteristic properties, in the upcoming period it will be more alluring for researchers and engineers working on several
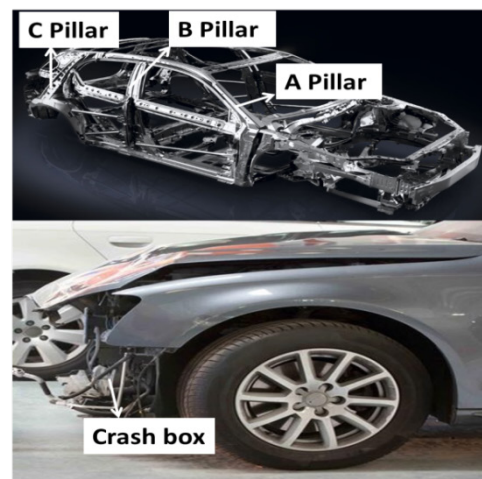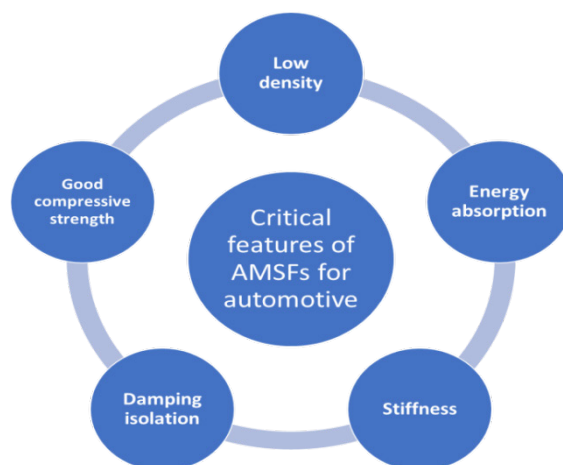

Figure 8. Probable AMSF application examples for automotive sector

industrial areas.

4. 5. CONCLUSION

In this paper, AMSF materials were reviewed elaborately with regards to their fabrication, physical features and mechanical responses by collecting and comparing many different literature studies. Moreover, we aimed to bring out some application suggestions for probable future works. As a result of our effort, the followings given below can be put in order;

- AMSF is an advanced engineering material having both foam and composite nature due to hollow or porous ceramic filler materials.

- For AMSF fabrication, infiltration casting and dispersion casting techniques are preferred by majority of the researchers although powder metallurgical ways recently have been investigated.

- By the reason of the fact that AMSFs have low density, perfect plateau behavior, good energy absorption ability and high ductility, they performs perfect under the compressive loadings.

- Along with their quasi-static behaviors, AMSFs also display outstanding mechanical performance under the high strain rate deformation. This situation is highly promising for their impact loading and damping isolation applications.

- Apart from their compressive properties, other types of loadings like fatigue, bending and creep have not been studied decently on AMSFs and we consider that this may alter in the immediate future.

- Almost all of the AMSF fabrication studies have been carried out on a lab scale and limited with simple cylindrical shape, however, in order to meet the requirements of industrial applications, some secondary machining processes or advanced casting techniques should be analyzed in the upcoming years.

- Compared to other sectors, automotive, aviation and construction industries are the most remarkable candidates for real applications of the AMSF. Together with the increasing studies about AMSFs, it is considerably possible that real AMSF parts will appear in land vehicles, aircrafts and modern buildings.

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