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Manufacturing and characterization of AlSi foams as core materials

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Abstract

AlSi alloys and their foaming properties have been studied in this paper. For adequate comparison it has been necessary to define process parameters and optimal chemical composition of the Al alloys. Such foams have been evaluated in terms of structure and mechanical properties, in particular in the use of foams as cores materials of cylindrical massive skins.

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Keywords: Al foams, mechanical properties, core materials,

1. Introduction

During the expansion of the blowing agents in the molten metal, as usually happens in the compacted powder method [1], very large porous structures are frequently observed [2]. Such large pores are weak points for the structures [3] and, in some cases, are responsible of inadequate mechanical properties [4-5]. The premature gas-release, due to the phase-shift between the decomposition temperature of the blowing agent (TiH_2 for Al alloys) and the melting point of the alloy, is the main reason of formation for such cellular structure. An attempt to solve this problem is to provide a very fast heating of the precursor, for example setting the precursor at higher temperature than the melting point of the alloy in order to minimize the time elapsing between gas-release and precursor melting [6].

AlSi foam production of good quality is very attractive for the industry due to the increase of mechanical properties obtained by the Si presence as alloying element and density reduction of the alloy [7]. The first task of this work is to determine the alloy composition range and the process parameters that allow AlSi foam production of good quality and acceptable geometrical features [8-9]. Foams quality has been evaluated quantitatively by image analysis while mechanical properties have been investigated by means of static uniaxial compressive tests [10]. The

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evaluation of mechanical properties [11-13] in the use of foams as core materials inside AISI 304 pipes has been performed by static radial compressive tests. It has been necessary to select such test configuration in order to have foam stiffness comparable with steel pipe.

2. Materials and methods

2.1. Precursor manufacturing

Each precursor was produced by mixing AlSi alloy and Al powders with the addition of SiC powders (stabilizing agent) and TiH_2 (blowing agent). Four different AlSi alloys (AlSi6, AlSi8, AlSi10 and AlSi12) were manufactured in this study. The effect of the stabilizing agent content was investigated at four concentration levels (3, 6, 9 and 12%) while the blowing agent was tested at two different concentration levels (0,4 and 0,6%). The powders, properly mixed, were then inserted into a cylindrical mould and subjected to static uniaxial compression with a force of 15 kN. After extraction the precursor is ready to be foamed in the owen.

2.2. Foam expansion

The precursor, to be foamed inside the crucible, is inserted inside an oven at 700° C. If copper crucible is employed, time for foaming is about 5 minutes while using AISI 304 crucible at least 8 minutes are required. This difference is mainly due to the higher thermal conductivity of copper (K_{Cu}=335 W/m°C) if compared to the steel one ($K_{AISI304}$ =15 W/m°C) of the same thickness. When the foam reaches the maximum expansion the crucible is rapidly immersed in water at room temperature in order to solidify the foam structure. Finally foams are extracted from the crucible in the case of copper tube, while for AISI 304 tubes foams have been left inside. In order to improve the poor weldability between aluminium and stainless steel and to ensure the adherence of metal foam to the steel skin, a mechanical anchorage has been performed by turning the inner surface of the steel pipes. All the precursor have the same geometrical features (diameter 15 mm and height 9 mm). In this way the foam expansion can be evaluated by the analysis of the expansion inside the cylinder with fixed outer diameter (15 mm).

2.3. Structural characterization by image analysis

Morphological characterization of foams was performed by means of image analysis on the middle cross-section both on pure Al and AlSi alloys. It is considered of good quality the morphology of metal foams with a great number of small regular-sized pores is present. In order to quantify these features two different parameters have been defined and evaluated: equivalent diameter (Deq) and circularity (C).

Equivalent diameter is calculated as follow by indirect measurement of area of each pore, considered as a circle that circumscribes the equivalent surface of the pore itself. This parameter is evaluated by the following relation:

$$D_{eq} = \sqrt{4\frac{Area}{\pi}} \tag{1}$$

Circularity is derived from the geometric features of each pore and is unitary for a circular cavity. This parameter is evaluated by the following relation:

$$C = \frac{4\pi\, Area}{perimeter^2} \tag{2}$$

The best characteristics of a metal foam is the lower diameter equivalent (small pores) and the higher circularity (regular pore shape).

2.4. Compressive tests

Mechanical characterization of foams was performed by static uniaxial compressive tests. Due to the axial stiffness of stainless steel tube much greater than the axial stiffness of AlSi foams it is therefore difficult to capture the stiffening effect of foam as core-material. For this reason, the compressive test of stainless steel pipe has been

performed in a static radial manner as defined in the standard UNI EN 12390-6:2010 which prescribes calculation of stress and deformation according to the following equations [14-16]:

$$\begin{cases} \sigma y = -\dfrac{6P}{\pi D l} \\ \sigma x = \dfrac{2P}{\pi D l} \end{cases} \tag{3}$$

where l is the sample length along the axis. It is important to emphasize that the radial compression test is suitable only for the comparison of mechanical strength of different samples and not for their mechanical characterization which must be executed only by static uniaxial compression test. From these experimental results it has been possible to calculate, by numerical integration, the energy absorbed by metal foams during deformation in correspondence of 50% of superimposed deformation.

Deformation values were calculated on the basis of the diameter values along the direction of compression according to the following equation:

$$\varepsilon = (D_0\text{-}D)/D_0 \tag{4}$$

where D_0 is the initial diameter.

2.5. Metallographic analysis

Due to the abnormal mechanical behaviour showed by AlSi foams subjected to compressive tests it has been necessary to perform metallographic analysis in order to verify successful alloying in the molten metal inside the crucible. The cross sections of hypoeutectoid alloys have been subjected to grinding and polishing and successively chemical etched with an aqueous solution of hydrofluoric acid (10%) for 15 seconds. After etching the samples were observed by optical microscope (100X, 200X and 400X magnification) and scanning electron microscope.

3. Results

3.1. Foam expansion

The best results in terms of expansion were obtained by decreasing the Si content. Assuming the foam expansion as the most significant parameter, the most suitable alloys for the production of metal foams are AlSi6 and AlSi8; AlSi10 and AlSi12 showed insufficient growth (Fig. 1). By the way the expansion coefficient of AlSi foams has been found lower than Al foam.

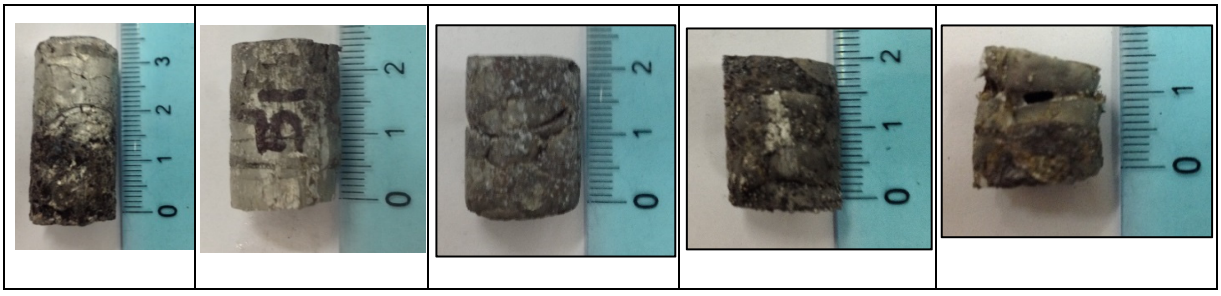

Fig. 1. foam in Al (a), in AlSi6 (b), AlSi8 (c), AlSi10 (d) and in AlSi12 (e). It is possible to observe the lower expansion with increasing silicon content present.

It should be noted that the greater expansion coefficient in AlSi foams was reached with 9% content of stabilizing agent, and a blowing agent equal to value of 0,4%. In particular, these values have been established taking into account also considerations regarding the pores morphology as discussed in the following.

3.2. Foam structure

It is well known that metal foams mechanical properties depend strongly on the pores morphology. In particular the best results in terms of mechanical characteristics can be obtained with a structure consisting in small-sized and regular-shaped morphology. These conditions have been easily achievable for pure Al foams, more troubles have been found in the definition of the process parameters for AlSi foams. For Al foams which showed the greatest growth, AlSi6 and in AlSi8 alloy foams, image analysis were performed and the results are reported in the following Fig. 2:

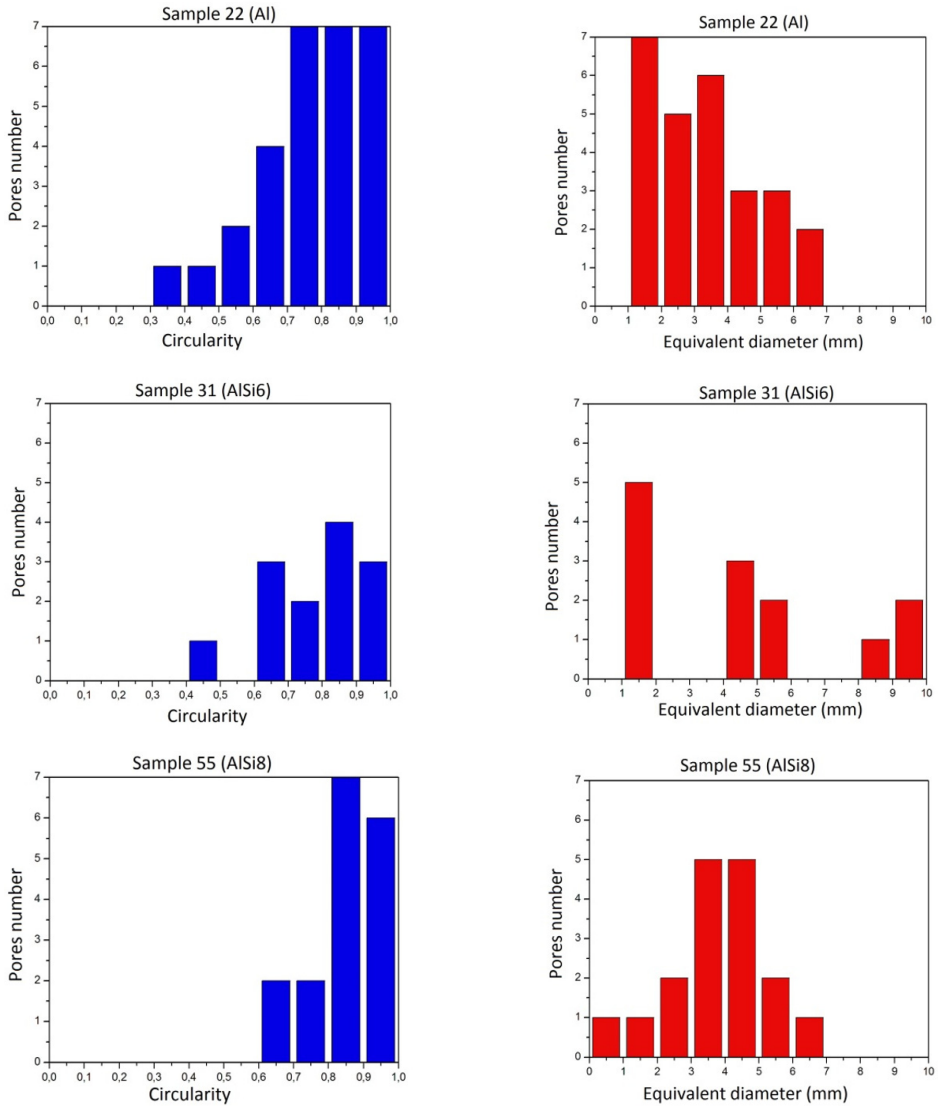

Fig. 2. equivalent diameter and circularity for a sample in Al (a), in AlSi6 (b) and in AlSi8 (c).

As reported in Fig. 2, pure Al foams present a very small equivalent diameter (70% of pores have an equivalent diameter less than 4 mm) and a high circularity (80% of pores have a circularity greater than 0,7). The equivalent diameter for AlSi6 foams is larger than pure aluminium (only 40% of pores have an equivalent diameter less than 4 mm), however good circularity (70% of pores have a circularity greater than 0,7) for AlSi foams has been achieved. AlSi8 foams show an equivalent diameter slightly greater than that in pure aluminium (55% of pores have an equivalent diameter less than 4 mm) and a circularity better than that in pure aluminium (88% of pores have a circularity greater than 0,7). According to these results the alloy which showed a quality comparable to the pure aluminium foam is AlSi8.

3.3. Mechanical properties of metal foams

AlSi metal foams were subjected to static uniaxial compression tests. Stress-strain curves obtained show the trend well known in literature: an initial elastic phase is followed by a stable phase characterized by the presence of a plastic plateau during which load is more or less constant. The final step is the densification of the foam characterized by a fast increase of load in correspondence with a small deformation increase. In Fig. 3 the compression curves for Al, AlSi6, AlSi8 and AlSi10 are reported.

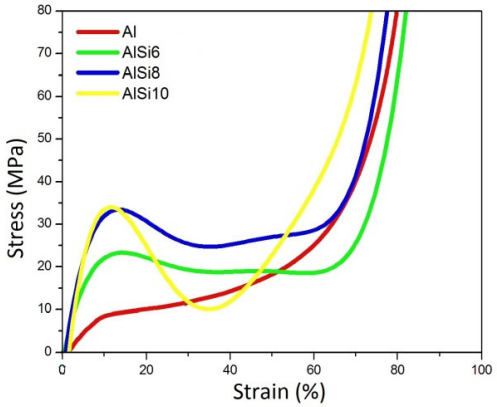

Fig. 3. compression curves of foams manufactured in different compositions.

As illustrated in Fig. 3, the higher the Si content the upper the mechanical characteristics of the foam, in terms of yielding strength and plateau stress. The last one is the most important characteristic in structural applications. For the highest Si content (AlSi10) an abrupt fall of the stress immediately after the beginning of the plateau has been observed. The consequences on the deformed samples are reported in Fig. 4: the higher the Si content, the more brittle the deformation way of the foam.

Fig. 4. pure Al (a), in AlSi6 (b) and in AlSi8 (c) foams after deformation.

In order to understand the causes of this behaviour metallographic analysis on the foam have been carried out.

3.4. Metallographic analysis of foams

Metallographic analysis were performed in hypoeutectoid AlSi alloy, in particular the AlSi8 (the alloy that has the best morphological quality of porous structure) has been investigated. As shown in Fig. 5 it is possible to identify some characteristics of this type of alloys: the presence of Al α phase (light) and the presence of the eutectic (dark) and the presence of SiC particles. These structures are clearly visible in the three optical micrographs made at three different magnification and indicated in the figure 5:

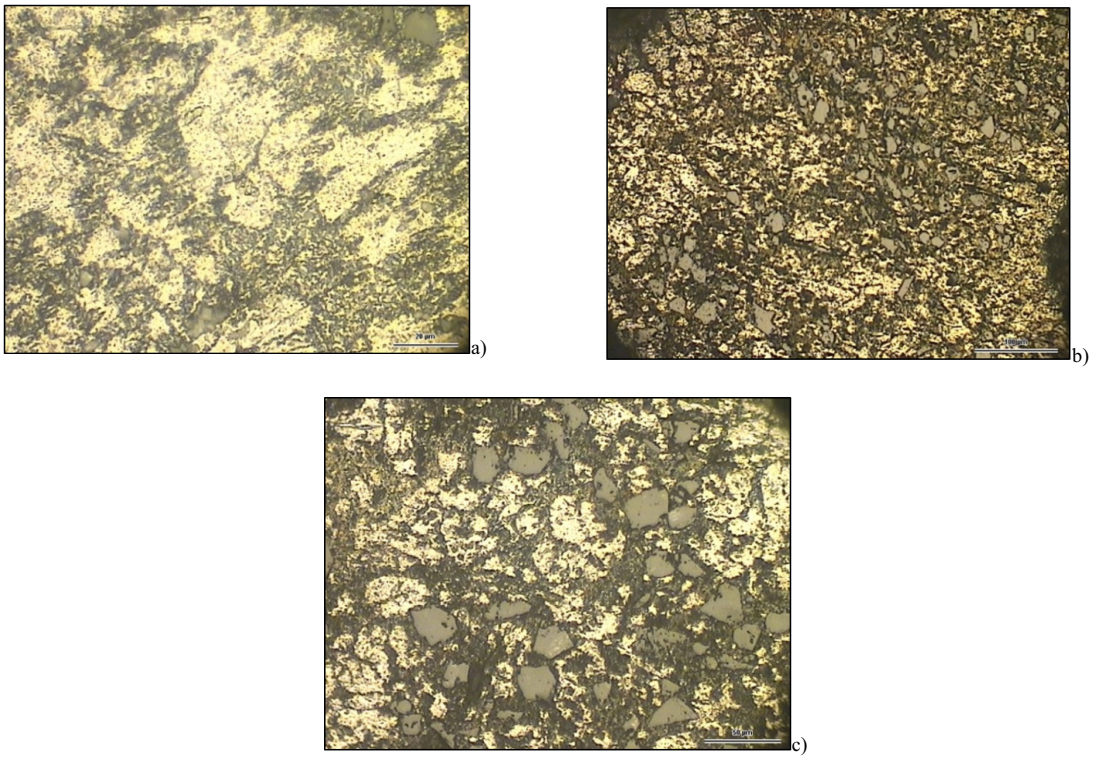

Fig. 5. micrographs of AlSi8 alloy with a magnification of 100X (a), 200X (b) e 400X (c).

From the micrographs in Fig. 5 it is possible to detect the presence of dark particles, large sized and irregular shaped. At higher magnification (SEM micrographs at 2.300X and 10.000X) more details are achievable on the nature of these particles. The edge-shape is a characteristic of SiC particles and the average size (30 μm) is the same of the SiC powder used in the manufacturing process. At the magnification of 10.000X are also detectable SiC particles of rounded shape and small size (1 μm). Both optical and electron scanning microscopy techniques shows that alloying of AlSi eutectic and pure Al powders has correctly happened in the melt and the lower ductility shown by the foams manufactured with high concentration of SiC can be ascribed to the different deformation way of the alloy.

3.5. Foams used as core materials

The stainless steel tubes were filled with pure aluminium foam, AlSi6 and AlSi8 foams and were subjected to static radial compression test. Stress-strain curves of filled-tubes, in comparison with the empty tube, are reported in fig. 6.

From compression curves reported in Fig. 6 can be evidenced the strength increase whichever type of filler was used: such increase is greater the higher the silicon content in the foam. The increase of the structure's strength, in

comparison with the empty tube, is paid in terms of increase of weight. In particular taking as references just empty tube, the percentage increase of strength and the percentage increase in weight that occur using the different foam filler can be evaluated.

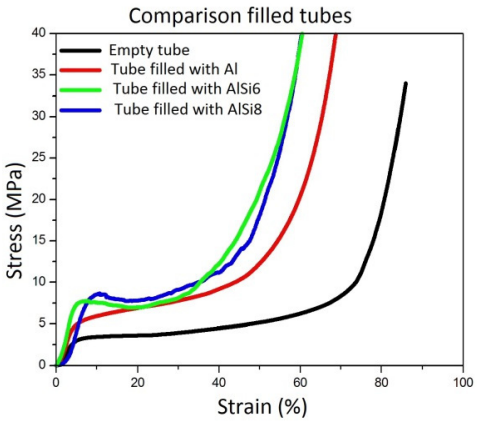

Fig. 6. compression curves of foams filled-tube for different composition of filler.

These percentage increases are shown in the following Fig. 7:

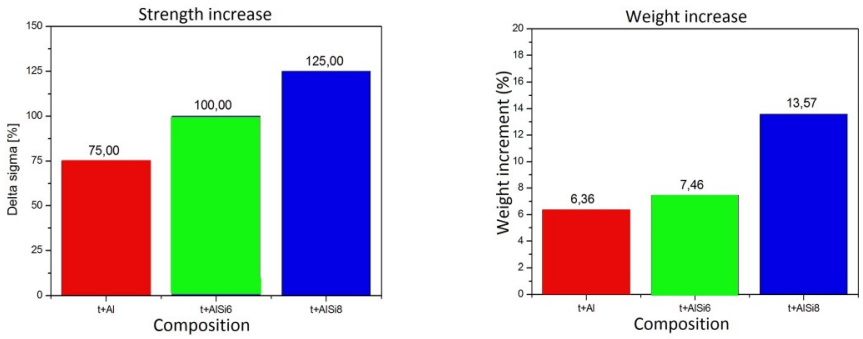

Figure 7: percentage increase of strength (a) and weight (b) compared to empty tube with different fillers used.

From data reported in Fig. 7 it is possible to observe that the strength increase with the Si content is accompanied by the corresponding weight increase. It is possible to define a dimensionless parameter (I = percentage increase of strength to percentage increase of weight ratio). For the three different fillers the following values have been found:

$I_{Al} = 11.79$
$I_{AlSi6} = 13.40$
$I_{AlSi8} = 9.21$

The choice of the most suitable filler must therefore be performed as a function of the particular properties to be achieved. In particular if the main objective is to increase mechanical strength the filler in AlSi8 ($\Delta\sigma$ is maximum) is the best choice while if the main objective is weight reduction the filler in pure aluminium (ΔP is minimal) is the optimal solution. The compromise solution will be a filler in AlSi6, as evidenced by the maximum value of parameter I.

Other important properties of metal foam is energy absorption during deformation. It has been calculated, by numerical integration, the specify energy consumption in correspondence of deformation of sample equal to 50%. The results are shown in the following Fig. 8:

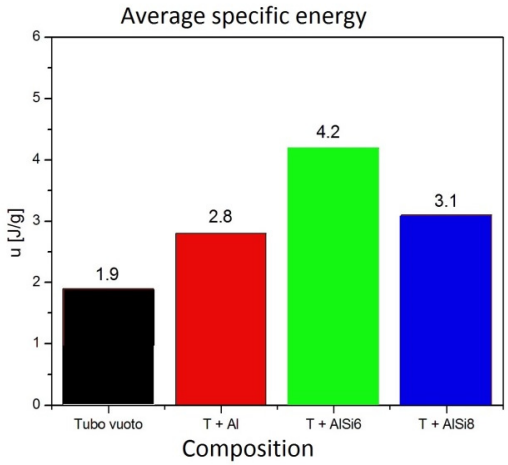

Fig. 8. energy absorption by the samples for 50% strain.

From Fig. 8 it is possible to observe, as expected, that the presence of a filler increase energy absorbed during deformation. Energy absorption does not grow with silicon content and a maximum value in correspondence of AlSi6 alloy can be observed. This circumstance can be justified taking into account that absorbed energy depends strongly on the porosity of the foam and is not maximum for massive sample.

As done for mechanical strength it is possible to calculate, in comparison with empty tube, the percentage increase of energy absorbed and the percentage increase of weight. These values are in Fig. 9:

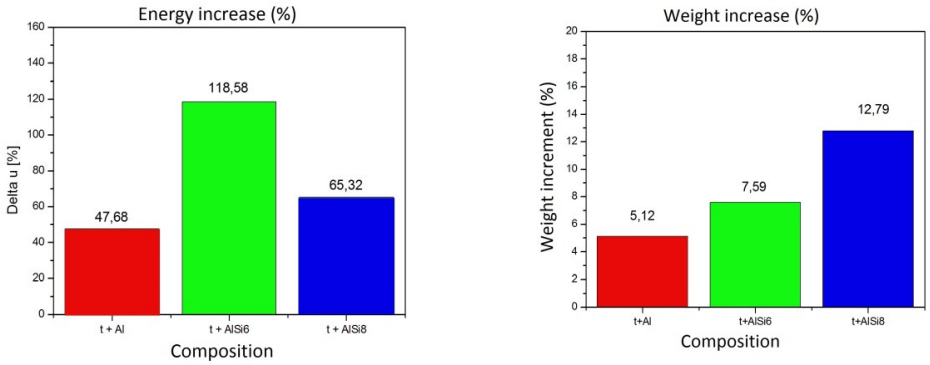

Fig. 9. percentage increase of energy absorption (a) and weight (b) in comparison with empty tube with different fillers.

From Fig. 9 it is possible to underline that as the maximum percentage energy increase has been found with filler in AlSi6 while the maximum percentage weight increase has been found with AlSi8. Also in this case it is useful to define a parameter E (percentage increase of energy absorbed to percentage increase of weight ratio). For the three different fillers the following values have been calculated:

$E_{Al} = 9.31$
$E_{AlSi6} = 15.62$
$E_{AlSi8} = 5.11$

From the obtained results it is easy to verify that for the purpose of energy absorption the filler in AlSi6 is the most powerful (I and E are maximum).

4. Conclusions

With methodology adopted have been manufactured the following foam alloys: AlSi6, AlSi8 and AlSi10 while AlSi12 alloy showed growth improvable. In order to manufacture foams in the indicated compositions were fixed the following process parameters:

Tab. 1. Powder composition and process parameters for the production of AlSi alloy foams.

Powders composition	Process parameters
9 % SiC	Pc = 15 kN
0.4 % TiH2	Tf=700

Foam's expansion was found to be inversely proportional to silicon content, however, as established by image analysis, the best result in terms of morphological structure quality has been obtained with AlSi8 alloy which is undoubtedly the best compromise between expansion and quality of structure.

The mechanical strength increases significantly with silicon content but this increase is paid with a moderate increase of density, and thus of weight for same volume, of structure. Using a filler in AlSi6 it is possible to have a strong increase of energy absorption with a small density increase.

During deformation AlSi foams showed a deformation way that, through metallographic analysis, can be considered due to the combined action of stress concentration and lower ductility intrinsic of alloy.

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