Failure mechanisms of aluminium foams under compressive loads

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The purpose of this paper is the investigation of the major failure mechanisms of aluminium foams, which were obtained by powder metallurgy route, under compressive loads. The study was focused on two commonly aluminium alloys AlMg1Si or A 6061 and AlSi12. Due to the fact that the failure mechanisms strongly depend on the density and the macrostructural properties of the material, the mechanical properties always have to be correlated to the structural properties. Therefore, macrostructural investigations were used as a basis to establish the correlation between structural and mechanical properties. This was done with a commercially available image analysis system. The average cell size, the cell size distribution and the cell density (number of cells/area) were obtained. In order to evaluate the influence of foaming direction on the cell morphology, some cross sections parallel to the foaming direction were prepared. For the characterization of the mechanical compression properties the compressive or upper yield strength (UYS), the densification strain (eD), the energy absorption (Ea) and the efficiency (Eff) were obtained. Furthermore, the failure behavior of the samples was in-situ observed with a digital video camera and continuously recorded during the test.

Key-words: Aluminum, foams, A-6061, AlSi12, compression properties.

Mecanismo de fallo de espumas de aluminio bajo cargas de compresión

El objetivo de este estudio es investigar los principales mecanismos de fallo de espumas de aluminio sometidas a cargas de compresión. Las espumas metálicas fueron obtenidas mediante el proceso pulvimetalúrgico, utilizándose como materia prima dos aleaciones comerciales AlMg1Si o A 6061 y AlSi12. Debido a que los mecanismos de fallo en este tipo de materiales depende fuertemente de la densidad y las características macroestructurales del material, en este estudio se busca correlacionar las propiedades mecánicas con estas características. La macroestructura se caracterizó mediante análisis de imagen. El tamaño de celda promedio, la distribución de tamaño y la densidad de celdas (número de celdas por área) fueron obtenidas en diferentes secciones transversales paralelas a la dirección de espumado. Mediante ensayos mecánicos de compresión se obtuvieron la resistencia a compresión o resistencia elástica superior (UYS), la deformación de densificación (eD), la energía absorbida (Ea) y la eficiencia (Eff). Los ensayos de compresión se grabaron mediante una cámara digital de vídeo realizándose su análisis posteriormente.

Palabras clave: Aluminio; espumas, A-6061, AlSi12, propiedades de compresión.

1. INTRODUCTION

The interesting combination of properties (light weight, good energy absorption, low thermal conductivity, recyclability, etc) of metal foams have spurred new process developments and optimization with the goal of to obtain materials with an optimize relation material properties-cost between material's properties and costs (1-6). One of the main advantages of the powder metallurgy route is the production of 3D near-net shape products which allows time reduction on the process and reduction of scrap material (7,8).

Because of most of possible applications of metal foams involve compression solicitations this work was focused in the study of two new metal foams, based in two commonly alloys A6061 and AlSi₁₂, by uniaxial compression.

2. EXPERIMENTAL PROCEDURE

2.1. Aluminum foam manufacturing and sample preparation

The aluminum foams were prepared by the powder metallurgy route following the parameters described by IFAM-Fraunhofer Researcher's patents (9, 10). The powders were mixed with a foaming agent (TiH₂), then the mixture is compacted or extruded to obtain rectangular sheets or cylindrical foamable semi-finished product. This product is inserted into a mould which is heated until up to temperatures close to the Al alloy melting point, the TiH₂ decomposes and H₂ gas is released producing the blowing mechanism. The bubbles cover all the and causes the expansion. Finally the foam occupies the whole mould producing a near-net shape product.

For this study 80x80x200 mm bricks of AlMg1Si (A 6061)

Figure 1. Material sampling and density comparison

and AlSi12 alloys with an average density of 0.55 and 0.57 g/cm³, respectively, were supplied.

Any heat treatment were applied on the materials after the foaming process. In order clearly define the three geometric directions according to the foaming direction, the three letters S, L and T were chosen. The foaming direction (S) is perpendicular to 200x80 mm surface and was indicated on each brick by an arrow, the L direction coincide to largest brick dimension and W with S. L direction is perpendicular to S and coincide to the largest brick dimension. T is perpendicular to S and T. The plane between two directions is indicated LS plane (figure 1). Thus TS plane was defined too, with the corresponding letters of the two directions, e.g. TS, LS (see Figure 1.).

Three cubic specimens of 60x60x60 mm were cut out from the center of each brick (MIDDLE, L1 and L2) and the upper and lower skins areas were removed too by spark erosion. This process avoid cell and surface damage, obtained samples have good tolerances and parallel surfaces, which allows uniform load distribution over the entire sample surface during the compression test.

Figure 1. shows the area from where the cubic samples were obtained and the density (ρ) variation on both alloys, it can be observed the following:

- Density of the MIDDLE is higher than L1 and L2 samples, thus means that there is not a uniform density distribution along the sample. samples.
- Density of lower skin area is the highest on both alloys, nevertheless on A 6061 alloy is quite similar to the density of upper skin area.
- AlSi12 has the maximum relative density variation $\Delta\rho/\rho_{(avg)}$ that is (highest – lowest density)/average density, and maximum relative standard deviation $S(\rho)/\rho_{(avg)}$.

TABLE I: AVERAGE COMPRESSION TEST RESULTS

	Direction	UYS (MPa)	C (MPa)	$\sigma_{50\%}$ (MPa)	$Ea_{50\%}$ (MJ/m ³)	$Ea_{50\%}$ (KJ/kg)	$\eta_{50\%}$ (%)	D (MPa)	eD (%)
A 6061 (AlMg1Si)	S	3,57	17	11,4	3,22	7,32	57	98	61
	L	6,44	15	12,5	4,2	9,92	67	101	61
	T	6,18	17	13,5	4,41	9,86	66	98	59
AlSi12	S	6,29	18	14,9	4,88	9,75	65	93	59
	L	6,11	19	15,3	5,54	11,18	72	93	59
	T	4,02	24	16,3	5,19	9,60	65	86	67

Figure 2. Schematic stress-strain curve of a compression test.

- The density of cubic samples was around 78% and 90% of total brick density on alloys A 6061 and AlSi12, respectively. This relation could change depending on brick-sample dimensions and sampling.

2.2. Compression test

The cubic specimens were tested according to the compression test standard prepared in the METEOR project (11) based on ASTM C 367, D1621 and DIN53421 standards (12-14). The main testing parameters are:

The load was applied by rigid load plates, which maintains their initial alignment throughout the entire loading process.

The cross head speed applied was 10% of sample thickness per minute

The compressive strain was obtained by means of load plates displacements

Figure 2 shows the different results that could be obtained on each compression test. For this paper the compressive or Upper Yield Strength (UYS), collapse plateau (C) and densification slopes (D), the Energy Absorption and Efficiency until 50% strain ($Ea_{50\%}$, $\eta_{50\%}$), and the compressive strength at 50% strain ($\sigma_{50\%}$) were shown. The results are the average of all samples tested (4 per direction and per alloy). Figure 3 shows a typical compressive stress-strain curve on the three testing directions (L, S, T) on studied samples, the specimen density is indicated between brackets.

The tests were carried out in an INSTRON 5500R universal testing machine, a video recording was done in order to analyze the failure sequence.

Figure 3. Compression stress-strain curves of A 6061 and AlSi₁₂ alloys.

2.3. Millistructure characterization (Cell structure characterization) characterization

In order to have more information about the material characteristics a cell structure characterization was carried out. The cell size distribution along two perpendicular cross-sections (TS and LS) through two bricks per alloy were analyzed. The study was carried out on the complete sample (100%) and was described previously (15). A total of six samples of 80x80x10 mm were obtained from two different bricks per alloy (3 on LS plane and 3 on TS plane).

Samples were cut by spark erosion in order to avoid cell wall damage and embedded in black resin. These mounted specimens were then ground and polished. The image of the polished cross-section was acquired by a TV camera and later processed to obtain an enhanced image.

The parameters obtained were average cell size or equivalent diameter (m), its standard deviation (s), cell density (NC/cm²) or number of cells per unit area and shape factor. The software used to analyze the images was Optimas 6.1 (16).

3. RESULTS AND DISCUSSION

3.1. Compression properties

The average compression test results are shown in table I, in order to include the sample's density influence on compression results specific values (property divided by density) are also shown.

The following conclusions could be done:

- Absolute values and specific results give in general similar comparative information.
- In general, in both materials, the compressive strength increases if the compressive strain increases. As an example, the compression strength at 50% ($\sigma_{50\%}$) is around two times the UYS.
- Both materials show a scattering of the UYS, e.g. the lowest UYS on A6061 and AlSi₁₂ are 44% and 36% lower than the highest values; however when $Ea_{50\%}$ is analyzed lower differences were found (26% and 12% on A6061 and AlSi₁₂ respectively).

Figure 4. Typical cell size (Equiv. Diameter) vs. Cell density distribution. Typical A6061 and AlSi₁₂ millistructures.

- The samples who have the lowest UYS usually have the highest collapse slope C and densification strain ϵ_D , which was over 59% on both alloys.
- The densification slope (D) tends to be similar between the three testing direction in each alloy.
- The lowest $Ea_{50\%}$ and Efficiencies were obtained on foaming (S) direction.

3.2. Structural analysis

Figure 4 shows typical cell size distribution in function of cell density, it is also showed the accumulated distribution. Table II shows the average results obtained after millistructure characterization of all the samples. The following conclusions could be obtained:

- All samples have some big cells, which are 6 or 7 times bigger than the average cell size. Moreover in some compression samples big cavities were observed too. These big cells or cavities can be considered as material defect, this characteristic justifies the high s values.
- Similar average cell size (m) values were obtained between all cross sections of each alloy. The low shape factor values confirms that in average the cell shape is not spherical, however there are areas where more spherical cells could be observed.
- Higher values of NC/cm^2 and shape factor were obtained on AlSi12 than on A 6061 material, moreover 95% of cell size have values lower than 3,1 mm and 3,7 mm on mentioned alloys. Thus means that higher densities are related with lower average cell size and higher NC/cm^2 .

Table III shows the density and cell size-shape variation between different material sections (40x40 mm, 22mm height), which were obtained when cubic samples were divided in three similar parts and ordered following the foaming direc-

tion thus „upper section“ means the area located in the top of the sample whereas „lower section“ means the area located in the bottom surface. AlSi12 foams shows a more uniform material distribution, cell size and shape factor per section than A6061 foams. Table III shows that lowest densities not always means highest average cell size.

3.3. Failure mechanism

Some studies focus on metal foams obtained by metal route over specific cross sections demonstrates that the failure star-

Figure 5. Typical failure mechanism during compressive loading: Compression loads produce initial local cells crushing and shearing. Deformation planes (left picture) are formed and samples increase width due to shear effects. Material A 6061 tested on L direction.

TABLE II: MILLISTRUCTURE AVERAGE RESULTS

Alloy	Plane	m (mm)	σ (mm)	NC/ cm ²	Shape factor	95% of cell size lower than
A 6061 (0,55 g/cm ³)	LS	1,4	1,2	20,29	0,675	3,8 mm
	TS	1,4	1,2	22,03	0,676	3,6 mm
AlSi ₁₂ (0,57 g/cm ³)	LS	1,2	0,9	27,57	0,691	3,1 mm
	TS	1,2	0,9	28,16	0,696	3,1 mm

TABLE III: DENSITY AND CELL SIZE PER SECTIONS

Alloy	Section (g/cm ³)	ρ	Shape factor	m (mm)	σ (mm)	σ / m (%)
A 6061 AlMg1Si	Upper	0,53	0,655	1,16	0,98	84
	Middle	0,38	0,625	1,43	1,16	81
	Lower	0,35	0,660	1,55	1,32	85
AlSi ₁₂	Upper	0,45	0,675	1,08	0,80	74
	Middle	0,465	0,667	1,30	0,94	72
	Lower	0,40	0,680	1,28	0,88	77

ted as a pure cell crushing (17) other models use as a reference the honeycombs behavior under compression loads (18), it was also observed that the failure surface was located on the middle area or section on samples tested under shear loads (15). After the analysis of the videos obtained during the compression test, it was observed that there is not a preferred area or region where the failure starts, many factors as mould shape, preformed material distribution inside the mould, foaming conditions, material alloy, foam defects, testing direction, sample characteristics, etc. make so randomly the determination of the area where the failure starts and support that failure process is a mixed mechanism of crushing and shearing of cells, because of the interaction of mentioned factors.

Figure 5 shows typical failure mechanism on material A 6061. Failure starts in a non linear band, that means that the surface of failure is not parallel to the load plates surfaces and follows an intricate 3D surface where cells fails by a combined mechanism of crushing and shearing. As the homogeneity of the material increases the contribution of the crushing becomes more significant and the failure can be observed as a layer per layer progression. This effect was observed on some samples tested on S direction, there the failure sometimes started in a plane parallel and close to one load plate (where the material is more homogeneous and has highest shape factor as it was shown on table III), the failure progress layer by layer until stronger and/or lower resistance areas were contacted, hence failure progress as a crushing-shearing cell failure mechanism.

4. CONCLUSIONS

The failure mechanism is dominated in the initial stages by a crushing-shearing cell failure associated to the interaction between non uniform material and cell size distribution and material's defects (cavities). These characteristics do not allow an easy estimation on where the material failure starts and how it can be progress along the sample.

As the compression strain increases the mechanism tends to be similar as multiple indenters penetrating in the material, where the indenters are associated to material's regions or areas with more compression resistance and probably associated to highest located densities.

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