Mechanical properties of AlSi10MnMg matrix syntactic foams filled with lightweight expanded clay particles

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Abstract. Compression tests measured the mechanical properties of AlSi10MnMg matrix syntactic foams filled with lightweight expanded clay particles (LECAPs). The metal matrix syntactic foams were produced by low-pressure liquid state infiltration method. Two types of LECAPs were used during production. One with ~3 mm diameter and the other type with ~9 mm diameter. The samples were machined and heat treated. The T6 heat treatment caused a significant increase in the properties in terms of plateau strength and absorbed energy. Also, the heat treatment caused a different failure mode in the case of the LECAP-9, which is why the absorbed energy increased by ~50% compared to the as-cast sample.

1. Introduction

Metal matrix syntactic foams (MMSFs) are developed from the polymer matrix syntactic foams [1]. In these foams, the porosity is created by previously produced materials such as hollow spheres or lightweight particles. Due to their low density, the syntactic foams are getting more attention because the parts created by these kinds of materials are usually more energy-efficient than the bulk ones, which is one of the main goals nowadays [2].

MMSFs are widely investigated in the literature. Mainly the compressive properties are measured [3-12], but in some cases, the tension [13], wear [14-16] or bending properties [17-18] are also determined. Another large investigation field is the thermal properties of these kinds of materials [19-22].

Regarding the filler materials, mainly the relatively expensive ceramic hollow spheres are used. For example, Su et al [23] investigated an alumina-aluminum matrix syntactic foam filled thin-walled tubes. Three different sphere sizes were investigated, namely 1.0–1.5 mm (a), 1.5–2.0 mm (b) and 2.5–3.0 mm (c). The matrix material was AlSi9Cu2Mg (ZL111) aluminum alloy which can be heat treated, and they also investigated the effect of the T6 heat treatment on the mechanical properties of the produced foams and structures. The tube’s material was AlMg1SiCu (A6061) aluminum alloy, while the ceramic sphere’s material was Al2O3. Quasi-static axial and radial compression tests were performed on the syntactic foams, on the hollow tubes and also when a syntactic foam sample was placed into the tube. Every test was repeated three times, and the results were averaged. The density of the produced foams are as follows: 2.01 ± 0.03 g/cm³ (a), 1.85 ± 0.01 g/cm³ (b) and 1.70 ± 0.01 g/cm³ (c). It can be seen that with the larger sphere, a lighter structure is achieved. The authors concluded from the mechanical
tests that the addition of the thin-walled tubes under axial compression the deformation and fracture mode were influenced and changed. It is caused a significant increase in energy absorption compared to the sum of the individual components. They proved that this kind of material compared to the literature’s data is a good choice for energy absorbers.

In the case of cheaper syntactic foams, one has to change the filler material. A good alternative for the hollow spheres is the lightweight expanded perlite. Movahedi et al. [24] investigated the influence of particle arrangement on the compression of functionally graded metal syntactic foams. Two different filler materials were used, namely expanded perlite (EP) and activated carbon (AC). The matrix material was a Zn-27Al-2Cu-0.015Mg (ZA27) zinc-aluminum alloy due to its high strength and relatively low density ($\rho = 5.00$ g cm$^{-3}$). Counter-gravity infiltration casting technique was used in order to produce metal matrix syntactic foams. Four different types of samples were produced based on the location and mixture of the filler materials: (a) two layer longitudinally-graded, (b) six layer longitudinally-graded, (c) radially-graded and (d) hybrid samples. Quasi-static compression tests were performed on these samples until ~80% strain. They found that the volumes of the samples which contain EP particles were undergone ductile layer-by-layer collapse while the regions with AC particles exhibit brittle fracture. Radial and hybrid samples had superior initial strength due to the fact that in these samples, the stronger AC particles must deform with the EP particles while in the layered structure the EP particles can deform separately.

Based on the previously presented studies, our aim was to find a low-cost alternative for the ceramic hollow spheres. Also, determine the influence of the heat treatment on the foams mechanical properties and deformation methods.

2. Materials and methods

2.1. Materials

AlSi10MnMg aluminum alloy was applied as matrix material due to the fact that this material is widely used in the automotive industry. The filler material was a set of lightweight expanded clay particles (LECAPs) which were obtained from Liapor GmbH & Co. KG. Two different sizes were investigated, namely ~3.2 mm diameter (LECAP-3) and ~9.0 mm diameter (LECAP-9). The size distribution was measured with an Olympus SZX16 stereomicroscope on 100 particles from each type, and the results are depicted in Figures 1. and 2., respectively. The materials chemical composition is listed in Table 1.

![Figure 1. The size distribution of the LECAP-3 filler. The average diameter is 3.2 mm.](image1)

![Figure 2. The size distribution of the LECAP-9 filler. The average diameter is 9.0 mm.](image2)
an induction furnace. The samples for the compression tests were machined according to the ruling standard for porous and cellular metals [26]. The LECAP-9 samples were 70×70×70 mm cubes and the LECAP-3 had 30 mm diameter and 30 mm height. The difference between the shape of the samples is not relevant in terms of the results. Both the rectangular and cylindrical shaped specimens are satisfying the requirements of the standard [26]. The main reason behind the different shapes, is the difficulty of the machining, and these shapes could be produced with the least amount of machining.

Table 1. The chemical composition of AlSi10MnMg aluminium alloy and the LECAP in weight percent

| Chemical elements in weight percent | Matrix material: AlSi10MnMg | Filler material: LECAP-3 | LECAP-9 |
|-----------------------------------|-----------------------------|--------------------------|--------|
| Si                                | 10.4                        | 55.4                     | 49.1   |
| Mn                                | 0.7                         | 32.6                     | 12.8   |
| Mg                                | 0.4                         | 7.6                      | 22.8   |
| Fe                                | 0.15                        | 2.4                      | 7.7    |
| Cu                                | 0.03                        |                          |        |
| Zn                                | 0.07                        |                          |        |
| Ti                                | 0.15                        |                          |        |
| Al                                | Balance                     | Balance                  | Balance|

Half of the produced samples were measured as cast, and the other half in heat treated condition. The first step was a solution heat treatment on 500°C for 3 hours and cooling in water. The second step was aging at 190°C and cooling in air.

2.2. Compression test procedure

The samples were measured on a 400 kN ZWICK/Roell Z 400 electromechanical test machine. Every compression test was performed under quasi-static conditions; the deformation rate was 0.01 s⁻¹. A compression tool was used to maintain the uni-axial deformation state during the whole compression until the samples reached 50% strain. Figure 3. shows the measurement setup in the case of a LECAP-9 sample. During the measurement, the force – displacement curve was registered and later the structural stiffness (S), the yield strength (σ_Y), the plateau strength (σ_plt) and the absorbed energy until 50% strain (W_{50%}) were evaluated according to the standard [26].

3. Results and discussion

Three samples were measured from every different type and heat treated foams, namely LECAP-3 (as cast), LECAP-3-T6, LECAP-9 (as cast), LECAP-9-T6. Figures 4. and 5. depict the results from the compression tests. It can be seen that the T6 heat treated samples have superior mechanical properties.
than the ones without heat treatment. Also, the foams with the larger filler particles have better mechanical properties.

![Figure 4. Engineering stress – engineering strain curve of the LECAP-3 and LECAP-3-T6 samples with error](image1)

![Figure 5. Engineering stress – engineering strain curve of the LECAP-9 and LECAP-9-T6 samples with error](image2)

It can be seen that in the case of the LECAP-3, the error is much larger, which can be caused by the fracture of the samples. Every type of sample fractured during the compression except the LECAP-9-T6 samples, that is why the error is much lower in that case. Also, because of the different deformation method, it exceeds higher stresses than the other samples. Table 2. contains the characteristic values and the coefficients of standard deviation (CoSD) calculated from the engineering stress – engineering strain diagrams according to the standard [26].

**Table 2. The mechanical properties of the LECAP filled syntactic foams according to the standard [26]**

| Name       | $S$ (MPa) | CoSD | $\sigma_Y$ (MPa) | CoSD | $\sigma_{plt}$ (MPa) | CoSD | $W_{50\%}$ (J/cm$^3$) | CoSD |
|------------|-----------|------|------------------|------|----------------------|------|------------------------|------|
| LECAP-3    | 1563 ± 147| 0.09 | 22.7 ± 3.4       | 0.15 | 25.7 ± 2.1           | 0.08 | 12.2 ± 1.3             | 0.11 |
| LECAP-3-T6 | 1582 ± 321| 0.20 | 28.1 ± 10.6      | 0.38 | 28.5 ± 9.5           | 0.33 | 13.8 ± 4.5             | 0.33 |
| LECAP-9    | 1162 ± 91 | 0.08 | 24.3 ± 3.6       | 0.15 | 26.8 ± 3.9           | 0.15 | 14.5 ± 1.8             | 0.12 |
| LECAP-9-T6 | 1179 ± 64 | 0.05 | 27.1 ± 2.1       | 0.08 | 43.5 ± 3.0           | 0.07 | 20.3 ± 1.2             | 0.06 |

The structural stiffness was almost similar for the as cast and heat treated samples which means it does not depend on the heat treatment, but it depends on the filler size. In the case of the yield strength, the heat treated samples have higher values which were expected because the matrix material has higher yield strength with the T6 heat treatment. The plateau strength was following the same trend as the yield strength, but the LECAP-9-T6 exceed the expected values with 15 MPa, which can be caused by more plastic behaviour. This behaviour also influences the absorbed energy, which also became the highest in the case of the LECAP-9-T6. Figures 6. and 7. shows a LECAP-3-T6 and LECAP-9-T6 sample after the test, respectively.

Both samples got fractured, but from the LECAP-3-T6 samples, parts are missing due to the fractures. Every other type got the same failure type like this one. The integrity of the samples was lost during the compression, but the LECAP-9-T6 samples were not. In Figure 7., one can see that the walls between the fillers fractured, and the matrix material deformed plastically, but the integrity of the sample remained. This fracture mechanism is really useful in the perspective of energy absorption applications. Also, the high plateau strength and absorbed energy indicate that this low-cost filler material with the AlSi10MnMg aluminium alloy matrix material is a good choice for further investigations.
4. Conclusions

From the presented work, where two different particle ranges were investigated in as cast, and in T6 heat treated conditions, the following conclusions can be drawn:

(a) Expanded clay particles filled AlSi10MnMg aluminium alloy matrix syntactic foams were successfully produced by low-pressure infiltration technique.

(b) The T6 heat treated samples showed higher yield strength, plateau strength and absorbed energy.

(c) The LECAP-9-T6 samples had a different type of failure mode than the other types; namely, these samples got fractured at the thin walls between the filler particles, but they have preserved their integrity.

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