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Fabrication of In-situ Syntactic Aluminium Foam-Filled Steel Tubes

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Abstract

In all areas of industry, when choosing a material, compromises must be made since there is no material with all the properties that are preferential for any use. In the automotive sector, lighter and less dense materials can provide a considerable advantage, for example, lower fuel consumption due to weight reduction. Specialists dealing with materials science within metal foams have been trying to exploit the low density, high specific strength and high energy absorption capacity of metal foams in as many ways as possible for a long time. This research describes the one-step production method of syntactic metal foams with an aluminum matrix infiltrated into a thin-walled steel tube, intended to create functional structures with a strong adhesive bond and metal foam filling in a feasible way.

Keywords: *metal matrix syntactic foam, foam-filled tubes, low-pressure infiltration.*

1. Introduction

Syntactic metal foams are produced mainly by themselves and not as functional, structural elements [1–3]. Recently, however, more and more research has been dealing with metal foam-filled tubes (FFTs), which examine metal foams placed in tubes of a certain wall thickness. Because the properties of metal foams can be further increased if they are filled in hollow closed (metal) sections, the metal foam filling and the closed section surrounding it can support each other[4].

The tubes filled with metal foams are more resistant to different types of loads than the metal foams themselves. Compression and bending are the two most important stresses in such structures, which is why researchers mainly characterize foam-filled tubes with these properties. The production of these structures can be done in two ways: in one step, which is called the in-situ method or in multiple stages, which is called ex-situ. In the case of the in-situ method, the foam production process already takes place in the closed section. In contrast, in the case of the ex-situ method, the metal foam is reduced to the appropriate size after production, then placed in a pipe or fixed in some way.

Linul et al. [5, 6] investigated the effect of different temperatures on the axial quasi-static compaction of metal foams placed in circular tubes. The material of the foam was A356 (AlSi7Mg). The closed-cell foams were produced by stir casting and cut into Ø20×20 mm pieces. The density of the foams was 0.38–0.46 g/cm³. The specimens were placed in circular X5CrNi18-10 stainless steel tubes. Their outer dimensions were Ø22×20 mm, with a wall thickness of 1 mm, without any adhesive. In that research, quasi-static compression tests were performed with a crosshead speed of 10 mm/min at room temperature and elevated temperatures (150°C, 300°C and 450°C). The compressed specimens were examined by scanning electron microscopy (SEM) and optical microscopy (OM) methods. As the temperature increased, the brittle behavior of the aluminum foam changed to a ductile one, and above 150°C, the peak stress difference between the empty tubes and the foam-filled tubes started to decrease due to the softening of the aluminum foam filling. It was also observed that the foam in the tube reduced the size and distribution of microcracks.

Only a few in-situ produced metal foam-filled tubes can be found in the scientific literature, detailed below.

Duarte et al [7] manufactured closed-cell AlSi7 foams with a solid aluminum skin using the powder compact foaming technique by placing the foamable precursor in an AlMgSi0.5 tube and holding it there at 700°C for 12 minutes. The manufacturing method resulted in a tight fit of the foam but reduced strength and energy absorption due to quasi-static and dynamic axial compression in the tube material.

Kemény et al. [8] manufactured samples created in one step by low-pressure infiltration, where the molten matrix material (AlSi12) was poured directly into an AlMgSi0.5 tube filled with expanded clay aggregates. The small difference in melting point of the matrix and the tube material required precise adjustment of the infiltration parameters. The outer diameter of the produced specimens was Ø50 mm, and the inner diameter was Ø40 mm. The manufacturing process in that research is very similar to the process used in the present research; however, an important difference is the material and wall thickness of the tube used during the one-step production, as well as the difference in the equipment used.

Chilla [9] and his research group investigated X2CrNiMo17-12-2 stainless steel tubes filled with closed-cell aluminum foam. The outer dimensions were Ø31.7×100 mm, and the wall thickness was 1.85 mm. Three types of test specimens were produced; in the first type, the metal foam was ex-situ inserted into the steel tube with a tight fit; in the second type of test specimens, the aluminum precursor was placed in the tube before foaming and foamed there, intending to form cohesion between the foam material and the tube material. In the third type of specimen, the inner surface of the steel tubes was galvanized with copper before foaming in the tube so that the copper layer promoted the formation of a strong bond between the foam and the tube. This was proven to be a successful procedure since after the aluminum foaming, the continuous copper coating disappeared, and a reaction product was formed on the interface between the foam and the pipe, which also contained aluminum, copper, tin and tin with iron.

Taherishargh et al. [10] produced syntactic metal foams filled into tubes in one step using the vacuum infiltration method. The specimens were made from an AlSi7Mg matrix and 2.0–2.8 mm expanded perlite particles. The infiltration took place inside X5CrNi18-10 stainless steel tubes, which had an outer diameter of Ø25.4 mm and a wall thickness of 0.9 mm and 1.2 mm. The specimens were examined with computed tomography (CT) and energy dispersive X-ray spectrometer (EDS) and were subjected to quasi-static axial compression and a three-point bend test. For compression, the crosshead speed was 3 mm/min, and for the bend tests, 0.1 mm/s and 284 mm/s crosshead speeds were applied up to 30 mm displacement. The overall properties of the 0.9 mm wall specimens were better, and EDS confirmed the bond between the matrix and the tube. The tensile strength was estimated based on flexural properties.

Movahedi and his research group [11] produced structures with circular tubes of Ø28×30 mm outer dimensions surrounded by syntactic metal foam. The specimens were produced in one step by counter-gravity infiltration, using Zn27Al-2Cu0.015Mg alloy, 2.0–2.8 mm expanded perlite aggregates and AlMgSi0.5 tubes. A tube with Ø12×36 mm outer dimensions and a wall thickness of 1.6 mm was placed in the mould's centre before infiltration, surrounded by expanded perlite particles. Scanning electron microscopy (SEM) images showed a tight fit between the tube and the matrix material, but EDS analysis showed no chemical reaction at the interface.

2. Materials and methods

During the research, in-situ syntactic metal foam-filled tubes were produced from an aluminum alloy matrix (Al-Si10MnMg – Silafont-36) and mild steel (S235) tubes, which had a wall thickness of 1 mm and an outer diameter of Ø30 mm. Lightweight expanded clay aggregate particles (LECAP) sold by Liapor GmbH & Co. KG were used as fillers.

3. In-situ manufacturing

The manufacturing process was managed with the assistance of pre-manufactured steel crucibles, which were 40×50 mm cross-section, 280 mm high rectangular-based, hollow section crucibles, and a thin-walled steel tube was welded inside to the center of their base (**Figure 1**). The manufacturing process began with coating the inside of the steel crucibles and the outer surface of the welded steel tube with graphite emulsion. Then, the space between the outlet tube section that was welded to the side of the steel crucible and the thin-walled steel tube in the steel crucible was filled with alumina padding to prevent the melt from flowing through. There was also an outlet on the side of the thin-walled steel tube. The gap between the section and the tube was filled with aluminum padding up to a height of ~5 mm from the top of the outlet. After that, casting sand was used to fill the gap to the top of the inner tube, made of sand, bentonite and water. The function of the casting sand was to stop the molten aluminum from flowing between the tube and the section wall, thus avoiding an unnecessary amount of material adhering to the FFT. Due to the high thermal load capacity of the sand, it will not stick to the steel tube, so that it can be easily cleaned from the surface after casting. Another layer of alumina padding was placed around the upper part of the inner tube on top of the sand layer. The inner steel tube was filled with LECAPs with a diameter of Ø3.5–4.0 mm, and fixed in place with a stainless steel net on top, which prevents the displacement and floating of the LECAPs to the surface.

The steel crucibles were then placed in a Lindberg/Blue M furnace for preheating and heated to 400°C. The crucibles were kept at this temperature in the furnace for at least 45 minutes, so the temperature at all points was the same as that of the furnace. During the preheating, the AlSi10MnMg block serving as the matrix material was melted in an IND F-10 induction melting furnace until it was red. When it reached this condition, the induction furnace was turned off, and while the molten aluminum was cooling, the temperature of the melt was measured using a Maxthermo MD-3003 type K digital thermometer. In the used matrix material – filler particle – thin-walled steel tube system, a melt temperature of 820°C was necessary for successful fabrication, so the infiltration took place completely, even with the low preheating temperature. The pressure required for infiltration was applied to the crucible through a well-insulated pipe. The pressure came from a high-pressure argon bottle through a reducer, and a pressure of 0.4 MPa was used to press down the molten matrix material. After infiltration, the crucible was cooled under running cold water, then the outer crucible was removed, and in-situ FFTs in the state shown in the picture below (**Figure 2**) were obtained.

Finally, the unnecessary aluminum was cut off from the top of the steel tube, resulting in a syntactic metal foam-filled functional structure produced in one step. The cross-sectional view can be seen in **Figure 3**.

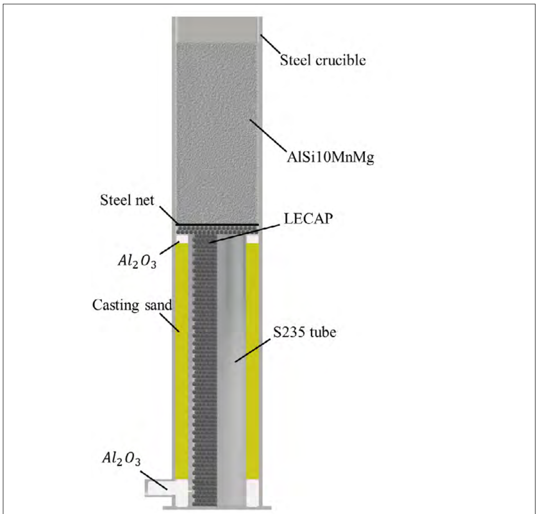

Figure 1. *Schematic figure of the in-situ foam-filled steel tube production.*

Figure 2. *In-situ produced syntactic metal foam-filled steel tube, after cooling.*

Figure 3. *Thin-walled in-situ syntactic FFT.*

The bulk density of the structure was determined based on geometric and mass measurements; its value was 2.30 ± 0.01 g/cm³, which is ~15% less than the density of the aluminium alloy used, and ~70% less than the density of the steel tube.

4. Conclusions

The following conclusions were drawn from the results of the research:

- low-pressure infiltration is a suitable melt route process for the one-step production of syntactic metal foam-filled steel tubes;
- during the research, a suitable mold was created for production;
- as a result, a functional structure was obtained with low density, which only needs to be cut before installation;
- further research of the manufactured structure is expected, primarily mapping its compression and bending properties based on the methods found in the literature.

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