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Particle Reinforced, Open Cell Metal Foams

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Abstract

Salt replicated metal matrix foams are cellular materials with interconnected cells. These materials have some highly specific mechanical properties. They are capable of absorbing high amount of energy during compression. The main goal of this study was to increase these mechanical properties without drastically increasing density with the application of ceramic particles as reinforcing material. In this research salt-replicated metal foams with particle reinforced cell walls were successfully created with pressure infiltration. The energy absorption capacity, the plateau stress and in some cases the specific values were increased approximately by 10 % to 41 %. by particle reinforcement.

Keywords: *metallic foam, open cell foam, reinforcement material.*

1. Introduction

In recent decades one of the main lines of material science research has been to optimize the weight specific mechanical properties of engineering materials.

One of the main objectives of this is the lowering of weight and density with the application of porous, cellular materials **[1]**. These materials have low density and high energy absorption capacity **[2]**. Metal foams can be categorized into three main groups based on their cell structure: closed cell metal foams **[2]**, open cell foams**[2, 3]** and syntactic metal foams **[4–7]**.

Another solution is increasing the mechanical properties without drastically increasing the weight. These materials are composites, where the high density-high strength reinforcing material is embedded in the low density-low strength matrix, such as aluminium alloys. These reinforcing materials could be ceramic particles, such as alumina or silicon-carbide or fibers, like carbon fiber for example **[8–11]**.

There is only limited publication concerning the combination of these two solutions. In these sources ceramic particles were applied as reinforcement in syntactic aluminium matrix foams **[12, 13]**. During these studies it was concluded that the ceramic reinforcement increases the compressive strength but lowers the plateau stress and the amount of absorbed energy up to 50% engineering strain. Due to this, the application of ceramic reinforcement in metal matrix syntactic foams is only advantageous in particular cases **[12, 13]**.

In this study salt replicated metal matrix foams were created with ceramic particle reinforcement in their metallic struts, and the effect on the mechanical properties of this reinforcement were examined.

2. Materials and methods

2.1. Materials

Al99,5 aluminium was used as matrix material, the exact chemical composition (wt%) was: Al: 99.68; Si: 0.16; Fe: 0.1; Cu: 0.05; others: 0.01. The measurement was performed in a Zeiss EVO MA 10 scanning electron microscope and was obtained as the average of 4 different measurements.

Common road salt was used as cell forming owing to its low price and wide availability. Gradient salt was used with a grain-size of 2.6–3 mm, a picture of the cell forming captured with stereomicroscope is shown in Figure 1.a As reinforcement material alumina and silicon-carbide ceramic particles were used with the same 0.35–0.60 mm grain size, they are shown in Figure 1 b, c. Both were added in 20% of the volume of the matrix material. The reinforcing materials were acquired from Granit Grinding Wheel Ltd. [14].

Based on the microscope images, the average diameter of the salt particle was 2.73 ± 0.04 mm, the grainsize of the reinforcement is shown in Table 1.

2.2. Methods

The sample was produced with pressure infiltration in an infiltration furnace.

The cell forming and reinforcing materials were mixed by hand mixing method until they reached an desired level of mixing based on visual investigation. The mixture was poured into mould made of S235J steel with the outer dimensions of 60×60×300 mm. The inner side of the mould was coated with Dueci Electronic N 77 graphite spray. The different mixtures were placed on top of each other separated with paper separators. The installation was closed with AISI 304 steel net prevent the cell forming or the reinforcement material preventing the movement of the filler into the molten matrix during infiltration. On top of the steel net a 2 mm thick alumina quilt was placed. Then the matrix material was placed into the mould. A model of the installation configuration is shown in Figure 3.

The installation was placed into the infiltration furnace at 600°C for 1.5 hours until the vacuum built up to 10-4 Pa. Then the temperature was raised to 750°C and was maintained for 1 hour, Following this, the infiltration was performed with 5 bar argon gas for 5 seconds. The idealized temperature history of the infiltration is shown on Figure 4.

The installation was cooled in air and after it reached room temperature the sample was cut out from the mold with angle grinder. The sample was cut into specimens with the dimension of 20×20×30 mm (Figure 2) with a Struers Discotom-10 cutting machine.

Firstly, the specimens were soaked in water (continuously flowing), to dissolve the cell-forming material and thus form an open cell structure. One specimen from every type was selected for visual investigation. These specimens were grinded with P80 to P2500 silicon-carbide sandpaper with even distribution and polished with 3 µm di-

Table 1. *The grainsize of the used reinforcing materials*

Reinforcement material	Nominal diameter (mm)	Measured grainsize (mm)
Al_2O_3	0.35–0.60	0.52 ± 0.07
SiC	0.35–0.60	0.42 ± 0.06

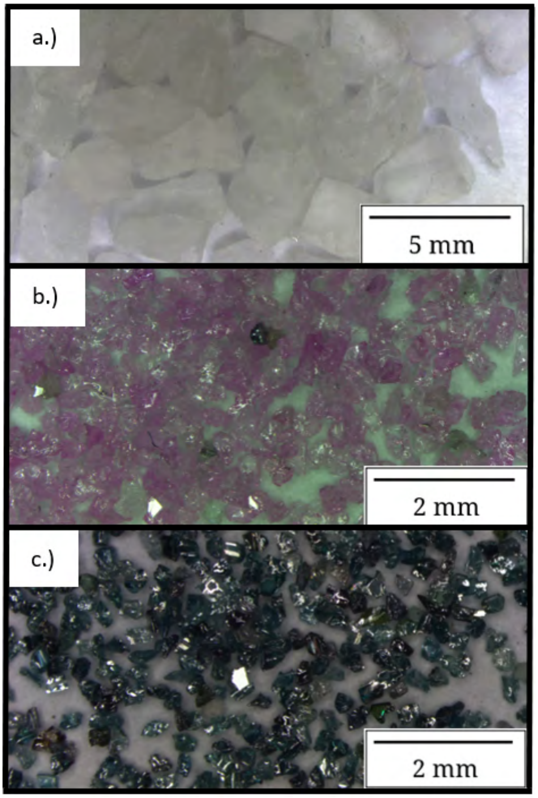

Figure 1. *a) Cell forming, b) alumina with grainsize of 0.35 – 0.60, c) silicon-carbide with grainsize of 0.35 – 0.60 reinforcement.*

Figure 2. *Picture of the specimens (from left to right open cell meta foam with Al_2O_3 reinforcement, Reinforcement metal foam by SiC and unreinforcement open cell metal foam.*

amond suspension. The investigation was carried out on an Olympus PMG 3 microscope.

The mechanical properties were examined with an MTS 810 universal material testing machine with a load bearing capacity of 250 kN, according to ISO 13314:2011 [15]. The tests were uni-axial quasi-static compression tests with 3 mm/min speed up to at least 50 % engineering strain. As lubrication, 0.3 mm thick Kolofol teflon foil was placed between the specimens and the faces of the machine.

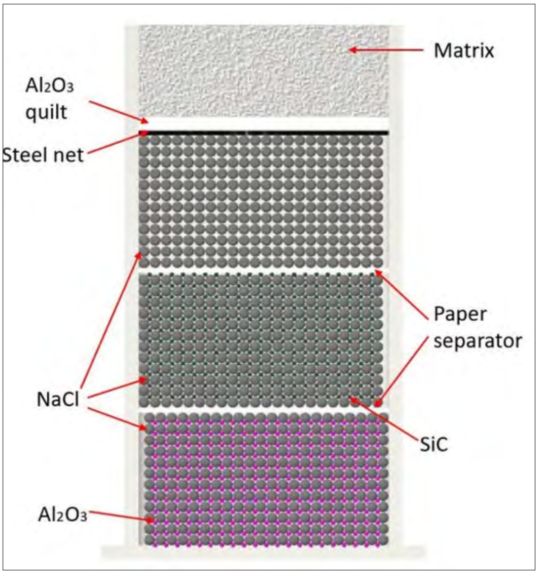

Figure 3. *Model of the installation which was used in our research.*

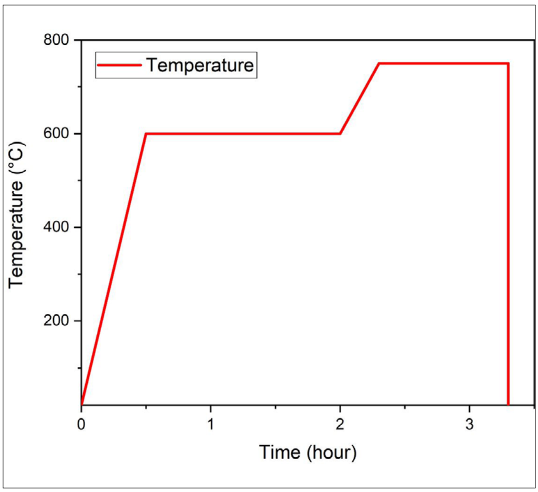

Figure 4. *The idealized temperature versus time curve.*

3. Results

3.1. Visual testing

The results of the micro-structural analysis are shown in Figure 5.

The micro-structural tests have shown that a good connection between the strut's material (acting as matrix in this case) and the reinforcing material has developed, and no large-scale porosities, surface defects, or separations have been observed. It is also clearly visible in the pictures that the salt was well dissolved, and the open-cell structure was formed. Based on these observations, pressure infiltration is an adequate method to produce salt replicated metal foams reinforced in the matrix material.

3.2. Mechanical tests

The force-crosshead displacement data pairs acquired during mechanical tests were transformed into engineering stress-engineering strain curves with the original cross section area and original height of the specimens. On these diagrams, the following mechanical properties and their den-

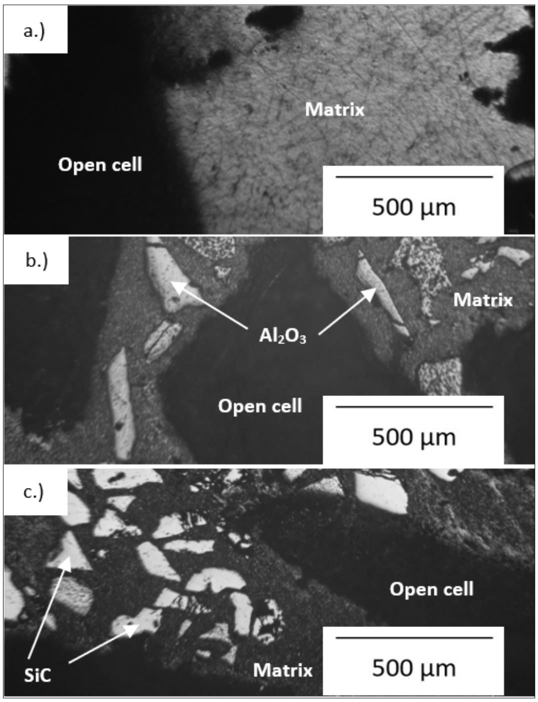

Figure 5. *Salt replicated foam reinforced with (a) alumina and (b) silicon-carbide (not every cell, particle of reinforcing material or matrix material is labelled).*

sity specific counterparts ('s' index) were examined: compressive offset stress ($\sigma_{p0,2}$, σ_{fpl1}), which is the stress at 1 % engineering strain, the plateau stress (σ_{pl}, σ_{fpl}), which is the average stress value between 20 % and 30 % engineering strain, and the absorbed energy in a unit of volume up to 50 % engineering strain (W_{50}, W_{f50}), which is the area under the engineering stress-engineering strain curve. These mechanical properties are represented in **Figure 6.**

The averaged curves of the three specimens of the same type and the absorbed energy in a unit of volume is shown in **Figure 7**.

The main mechanical properties are shown in **Table 2.** .

After evaluating the results, some of the mechanical properties can be improved by adding a reinforcement material. The density of the metal foams increased by 36% for Al_2O_3 and 19% for SiC.

As we can see. the application of reinforcing materials has increased the plateau strength, by 26% in the case of Al_2O_3 reinforcing material, and by 41% in the case of SiC. The energy absorbed up to a deformation of 50% increased by 24% and 36%, respectively.

However, the value of the conventional compressive yield strength was reduced by 11% in the case of silicon-carbide and increase by 27% by reinforcing Al_2O_3.

Examining the specific values, it can be concluded that both the plateau stress and absorbed energy increased by 13% and 10% by using the SiC reinforcing material, however, both parameters were decreased by 8% and 10% by application of Al_2O_3 -reinforcement, and the specific conventional compressive yield strength was decreased by an average 21%.

It can be concluded that silicon carbide performed well both in the case of plateau voltage and absorbed energy (and in their specific pairs as well) and improves these properties. Only the conventional yield strength and the specific conventional yield strength were not improved compared to the reference sample.

Out of the examined reinforcing material the usage of the silicon-carbide turned out to be the most advantageous.

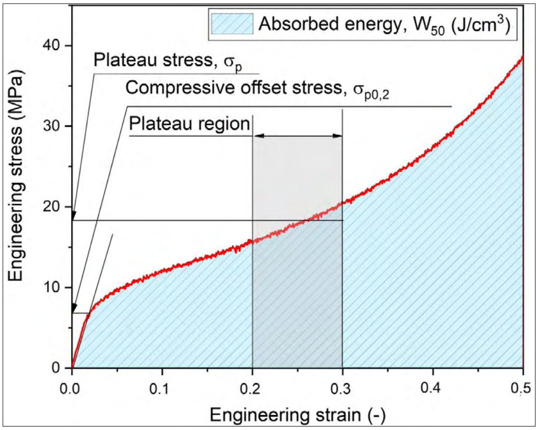

Figure 6. *The examined mechanical properties.*

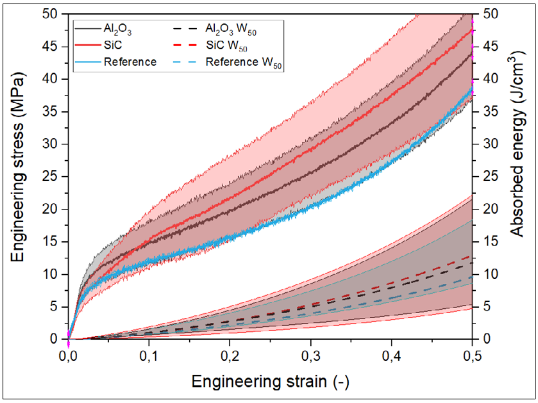

Figure 7. *The averaged engineering stress-strain curves and the averaged absorped energy curves of the specimens.*

Table 2. *Average values and standard deviations of the studied mechanical properties*

	σ_{pl1} (MPa)	σ_{pl} (MPa)	W_{50} (J/cm^3)
Ref.	6.40 ± 0.12	17.91 ± 0.19	9.66 ± 0.11
Al_2O_3	8.18 ± 0.52	22.93 ± 4.19	12 ± 97
SiC	5.78 ± 0.94	25.76 ± 6.18	13 ± 87
	σ_{fpl1} (MPa*cm^3/g)	σ_{fpl} (MPa*cm^3/g)	W_{f50} (J/g)
Ref.	5.40 ± 0.14	15.11 ± 0.16	8.15 ± 0.08
Al_2O_3	5.15 ± 0.27	14.08 ± 1.45	7.40 ± 0.63
SiC	3.98 ± 0.39	17.46 ± 2.81	8.94 ± 1.25
		Density (g/cm^3)	
Ref.		1.18 ± 0.01	
Al_2O_3		1.60 ± 0.12	
SiC		1.43 ± 0.11	

4. Conclusions

The following conclusions were drawn from this research:

– Pressure infiltration is an adequate method to produce salt replicated metal foams reinforced in the matrix material.
– Application of the Al_2O_3 reinforcing material were improved in the case of all parameters, however, in specific cases, the values for all parameters were decreased compared to the reference sample.
– In the case of silicon carbide type reinforcing material, the conventional yield strength and the specific conventional yield strength were improved compared to the unreinforced open-cell metal foam in all cases, except for the specific conventional yield strength.
– Out of the examined reinforcing material the usage of the silicon-carbide proved to be the most advantageous.

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