PROPERTIES OF ALUMINIUM FOAMS REINFORCED WITH CERAMIC PARTICLES

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Abstract

Aluminium foams are materials with a specific combination of properties due to their cellular structure. Unlike monolithic aluminium, foams have a significantly lower mass as a result of porosity. The higher it is, the lower the density and mass, but also the lower the mechanical properties. To improve the mechanical properties of aluminium foams, various ceramic particles can be used as reinforcements, whose content, size and distribution represent a significant factor. If the foam contains an excessive amount of reinforcement particles, it may become brittle. Also, nano-particle ceramic reinforcements tend to agglomerate, causing brittleness in cell wall areas. This article gives an overview of the properties of aluminium foams reinforced with particles of alumina (Al_2O_3), silicon carbide (SiC), titanium boride (TiB_2) and boron carbide (B_4C) with special emphasis on their compressive behavior.

Keywords: *aluminium foam, porosity, ceramic particles, compressive strength, energy apsorption*

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1. INTRODUCTION

During the production of aluminium foams, various problems can occur, such as insufficient viscosity of aluminium melt or the formation of cells of different sizes and shapes during cooling, which has a negative effect on mechanical properties. In order to increase the viscosity of the melt and thus stabilize the gas bubbles and enable the creation of a more uniform cellular structure, various ceramic particles are added to the melt or initial powder. These particles also have a beneficial effect on the compressive properties of foamed aluminium. Due to the accumulation of particles in the cell walls, foams with a high content of reinforcements are prone to brittle behavior under compressive load and are therefore not suitable for applications that require ductility. Foams with a high content of ceramic particles are more difficult to machine with higher production costs. Therefore, the usage of smaller ceramic particles that allow a larger number of reinforcements even at lower mass fractions is more acceptable [1]. Foams containing nanoparticle reinforcements cannot be produced by classical techniques, it is necessary to use advanced methods for their distribution, such as ultrasonic dispersion [1]. The addition of ceramic particles also increases the degree of expansion of the foam, which increases the number of pores and reduces the size of cells. However, in some reinforced foams, after reaching the expansion maximum, a fracture of a large number of cell walls occurs and the foam decays faster in the foaming process [2]. Figure 1 shows a diagram of expansion – foaming time for pure aluminium foam, and foams reinforced with 3 vol. % alumina (Al_2O_3), silicon carbide (SiC) or titanium boride (TiB_2), with particles of size ~10 µm.

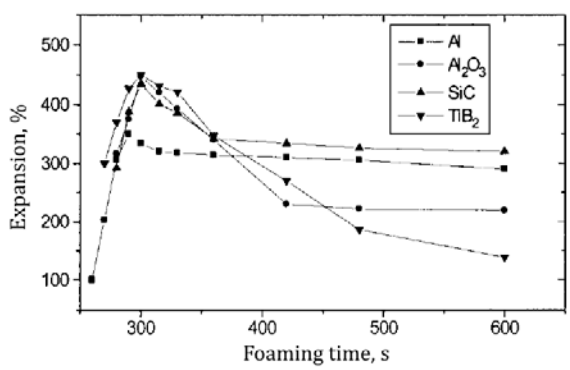

Fig. 1: Expansion – foaming time curve for aluminium foams reinforced with ceramic particles [2]

An increase in expansion degree due to the addition of ceramic particles was also found by Haesche et al. [3], they measured an expansion of almost 600 % in foams with 5 % Al_2O_3 and 5 % SiC additions, with particles of size 3 µm.

2. COMPRESSIVE PROPERTIES OF REINFORCED ALUMINIUM FOAMS

To evaluate the mechanical properties of aluminium foams, static compression test is usually performed with the recording of force – displacement diagram from which followed stress – strain diagram based on which the value of absorbed energy is calculated.

Rajak et al. [4] used a melt of aluminium alloy A360 (AlSi8Cu3Fe) to make foam, to which they added 5, 10 and 15 wt. % of SiC particles. Calcium carbonate ($CaCO_3$) was used as a foaming agent in the amount of 1, 3 and 5 wt. %. After testing the mechanical properties, they concluded that the most favorable ratio is 15 % SiC + 3 % $CaCO_3$. With such foam, the stress values in the compression tests were the highest, but it also had the highest density, as can be seen from the Figure 2, which should be considered when comparing the results. During the compression tests, SiC particles in the cell walls resist stress until its a critical value is reached, when fracture occurs near or at the cell boundary, so in foams with a higher content of reinforcements, a greater stress drop after reaching the initial maximum is visible.

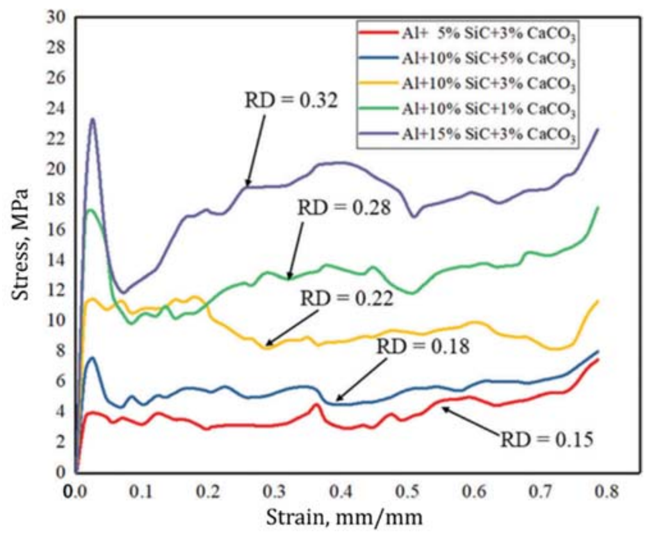

Fig. 2: Stress – strain diagrams of aluminium foams foamed with different amounts of $CaCO_3$ and reinforced with different amounts of SiC particles, *RD* = relative density [4]

In contrast to the approximately flat curve of the plateau region characteristic for the unreinforced foams, significant variations are visible in foams with particle reinforcements. This indicates that the foam does not show completely plastic behavior but tends to multiple local brittleness. With a larger addition of ceramic particles, the curve is more serrated due to the larger number of fragile areas. The reason is that SiC particles change the deformation mechanism of cell walls. During compressive loading, parts of the cell walls reinforced with particles cause sudden brittle fractures that cause a drop in the stress [4]. Similar correlations between stress and density of SiC-reinforced foams have also been reported in other articles [5-9].

Jaafar et al. [10] used aluminium melt for foaming to which they added different amounts of Al_2O_3 particles (1, 2 and 3 wt. %) to increase the viscosity and reduce the surface energy of the melt. Different content of foaming agent (3, 4 and 5 wt. % $CaCO_3$) was then added into the mixture and stirred for 40, 80 and 120 seconds, at a speed of 1400 rpm. For a combination of input parameters (contents of Al_2O_3 and $CaCO_3$, foaming temperatures ranging from 700 to 800 °C and stirring times), they used the Design of Experiment (*DOE*) and considered the results by the analysis of variance (*ANOVA*). The produced samples had a degree of porosity in the range of 70 to 82 %, and the compressive strength from 0.4 to 3.7 MPa. Analysis of variance found that all input parameters have a significant effect on the porosity level and compressive strength, and the most influential one was the content of $CaCO_3$. According to Figure 3, the sample with 3 % $CaCO_3$ had the lowest porosity and the highest compressive strength, especially for the highest Al_2O_3 content (3 wt. %). The highest porosity was recorded in the sample with 4 % $CaCO_3$, and with its further increase the porosity began to decrease, as shown in Figure 3a. A slight increase in the degree of porosity also occurs by increasing the Al_2O_3 content from 1 to 3 %.

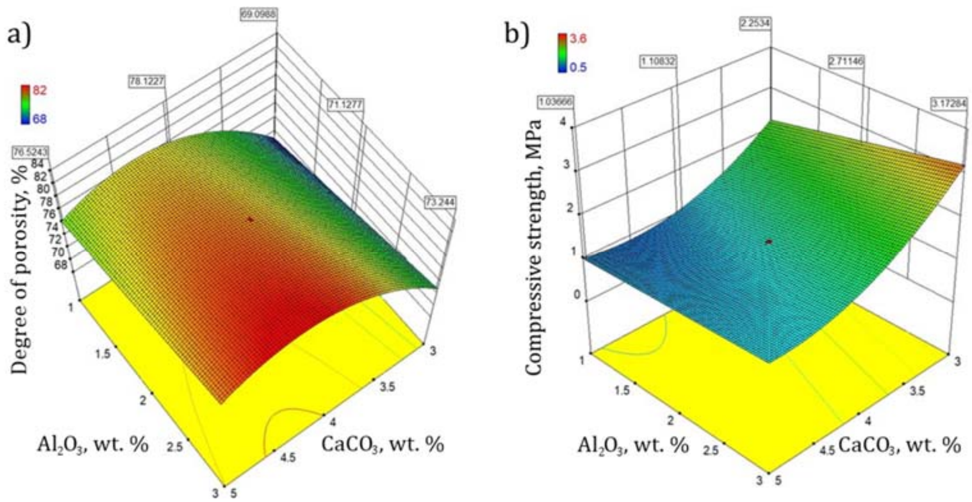

Fig. 3: Influence of $CaCO_3$ and Al_2O_3 content on the porosity degree (a) and compressive strength (b) of aluminium foam [10]

In Figure 4 it can be seen that the remaining two parameters, foaming temperature and stirring time, have a more pronounced effect on the porosity level and slightly less on compressive strength. Since the decomposition of $CaCO_3$ into calcium oxide (CaO) and carbon dioxide (CO_2) begins at 620 °C, foaming at 700 °C does not completely dissolve $CaCO_3$, so the porosity is lower than at the temperatures of 750 and 800 °C.

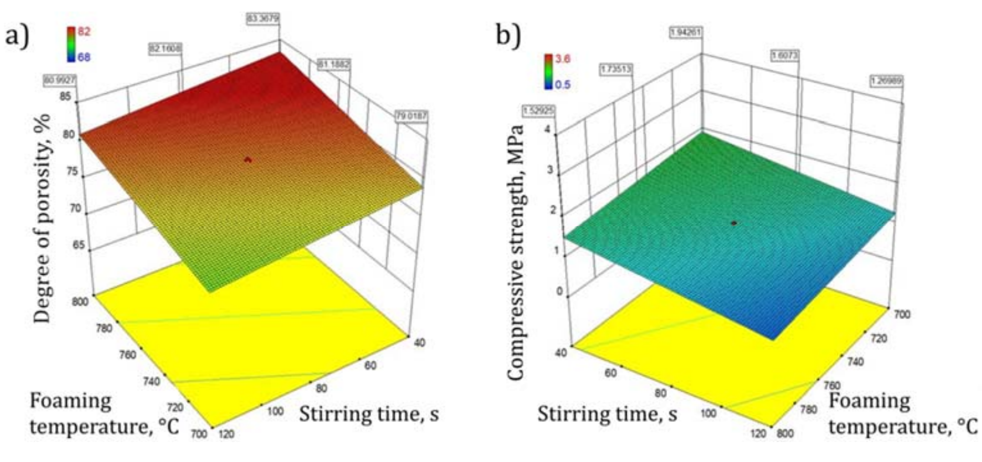

Fig. 4: Influence of foaming temperature and stirring time on the porosity degree (a) and compressive strength (b) of aluminium foam [10]

The relation between the input parameters and the obtained results can be presented by equations that define the porosity level and compressive strength. Such models can predict the properties of foam for any combination of parameters, provided that their values are within the limits determined by tests. Using the desirability function of multiple response, the optimal combination of parameters can be determined that ensures the highest porosity and the highest compressive strength [10].

It is known that the mechanical properties of metallic materials decrease with increasing temperature, which also occurs with metal foams. Dehnavi et al [11] investigated the compressive properties of aluminium foams reinforced with 3, 6 and 10 vol. % SiC particles at temperatures of 100, 200, 300 and 400 °C and comprehended that the properties vary significantly depending on the content of particles and test temperature. At each of the four temperatures, the highest values of plateau stress and specific energy absorption were recorded for a maximum reinforcement content of 10 %, Figure 5. They also confirmed that the presence of SiC particles implies an increase in cell wall thickness and thus greater bending resistance, especially at higher temperatures. Foams with a higher content of ceramic particles have proven to be more stable at elevated temperatures.

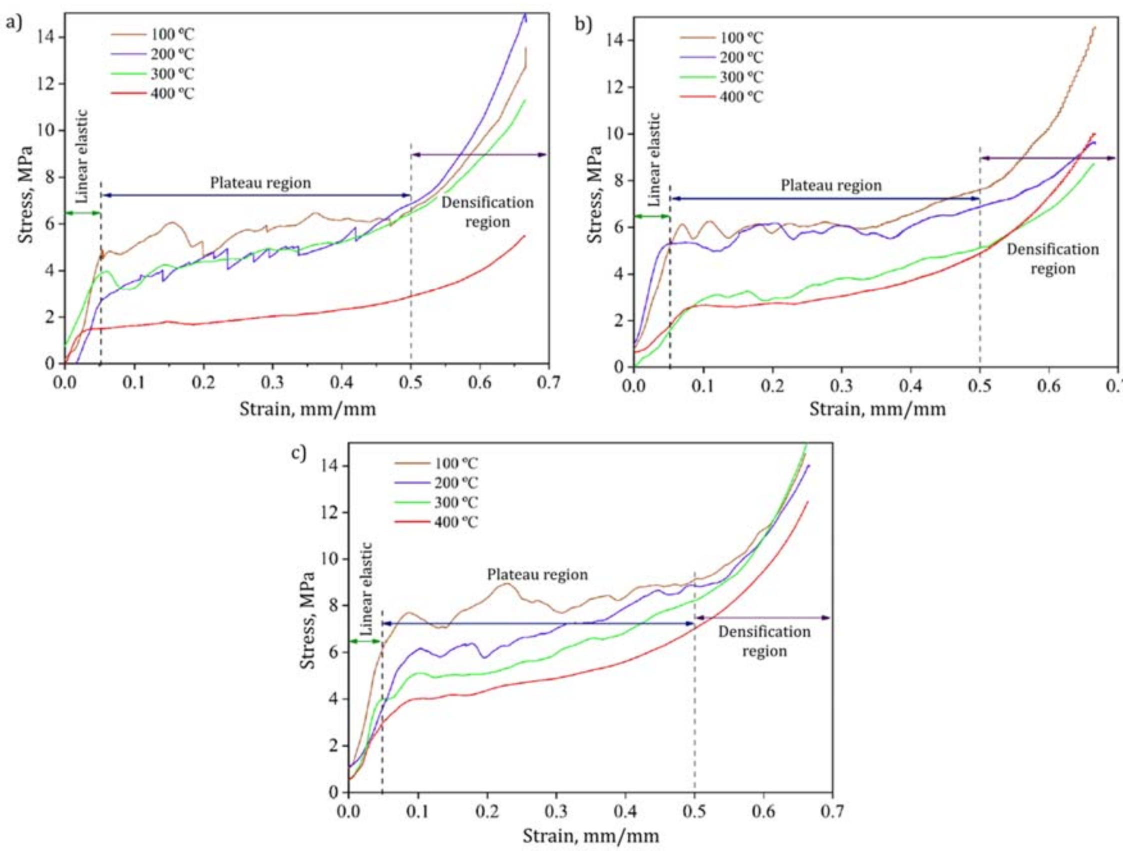

Fig. 5: Compressive properties of foams reinforced with 3 % SiC (a), 6 % SiC (b) and 10 % SiC (c) at elevated temperatures [11]

The properties of composite aluminium foams can be modified by heat treatment procedures as shown in [12]. Precipitation hardened aluminium foam with 10 vol. % SiC (solution annealed at 540 °C for 12 hours followed by quenching in water and then aged for 5 hours at 155 °C) can absorb more impact energy than untreated foam as a result of increasing the compressive strength.

Uzun [13] used SiC particles and carbon nanotubes (CNT) to reinforce Al foam with 2, 4 and 6 wt. % for SiC and 0.2, 0.5, 0.8 and 1 wt. % for CNT. As the plateau stress was not clearly expressed, the average stress R_{avr} at deformation from 0.2 to 0.3 mm/mm was calculated and found that the lowest value of this stress occurs in unreinforced foams, and with increasing proportion of both reinforcements its values grow. The highest R_{avr} in the amount of 37.67 MPa was obtained in the foam with 6 wt. % SiC and 1 wt. % CNT compared to 18.68 MPa for unreinforced foam. When analyzing these results, it should be considered that the addition of reinforcements also increases the relative density of the foam, which in this case varied from 0.352 for unreinforced foams to 0.417 for foams with the highest SiC+CNT content.

Singh et al. in [14] examined the behavior of foams containing 5 wt. % calcium (Ca) or boron carbide (B_4C) with the aim of increasing viscosity of aluminium melt. Foams with Ca content were elongated cells due to increased melt flow as opposed to foams with B_4C whose cells had almost spherical shape and higher relative density. Foam reinforced with B_4C particles show a higher compression strength, but also have a wavier curve due to the presence of hard and solid brittle ceramic particles in the cell walls, Figure 6. These particles create multiple interfaces with the metal matrix representing the crack initiators. Furthermore, foam stabilized with B_4C show a significantly higher energy absorption capacity of even 2.60 MJ/m^2 compared to 1.05 MJ/m^2 for calcium-stabilized foam.

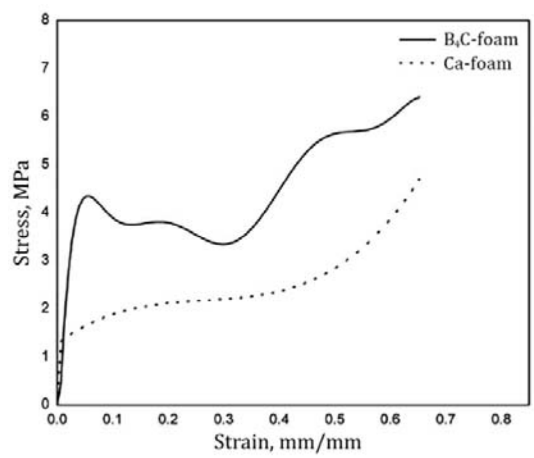

Fig. 6: Compressive properties of foams stabilized with Ca and B_4C [14]

Atturan et al. [15] produced foams by injection of 1.5 wt. % of heat-treated titanium hydride powder (TiH_2) into aluminium melt with 5 and 10 wt. % TiB_2 particles of size ~2 μm. It has been observed that foam with a lower content of TiB_2 expands better and it had a higher degree of cellular uniformity, but also more defects formed during solidification. In the following paper [16], they examined the compressive properties of the samples prepared in this way and found that the foam with 5% TiB_2 shows a higher plateau stress and better energy absorption capacity. Since the particles are very small (~2 μm), their significant grouping occurred at higher content (10 wt. %), which resulted in fragile areas in the cell walls.

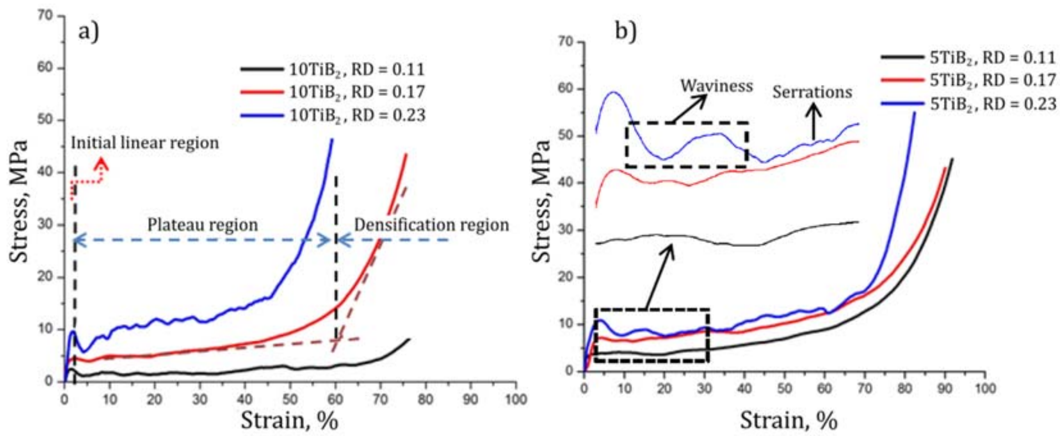

Fig. 7: Compressive properties of foams with 10 % TiB_2 (a) and 5 % TiB_2 (b) of different relative densities (*RD*) [16]

3. CONCLUSIONS

Research in the field of metal foams today is largely focused on improvement of their mechanical properties such as the compressive strength and the ability to absorb impact energy. To achieve this, various ceramic particles can be added to the foams. Recent studies have confirmed that the addition of a particles can improve the foam behavior in the foaming process and under compressive load, but it is necessary to consider the content, size, shape, distribution and type of particles, which all affect the properties of foamed metals. Today, alumina (Al_2O_3), silicon carbide (SiC), titanium boride (TiB_2) and boron carbide (B_4C) particles are most commonly used to stabilize and strengthen foams. Small particles are preferred, with the grain size in the nano-range, which even at lower content provide sufficient reinforcement without local fragility. Then the special attention should be paid to particles distribution due to tendency to accumulate and form agglomerates.

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