Effects of Production Parameters on Density and Tensile Properties of Aluminium MMC Foam

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Abstract

Aluminium foams, which may replace all the energy absorbing materials in near future, are produced by melting Aluminium alloy (LM6) containing blowing agent(s) and with continuous stirring of the melt. TiH_2 is a known blowing agent for this. As TiH2 begins to decompose into Ti and gaseous H_2 when heated above about 738K (465°C), large volumes of hydrogen gas are rapidly produced, creating bubbles that leads to manufacture of closed cell foam. A novel Strategy to enhance the light-weightiness and tensile properties of Al-MMC foams is discussed here, and it is demonstrated that titanium hydride (TiH_2) in the form of 10-15 μm diameter particles can be pre-treated by selective oxidation to produce more uniform foams having better physical and mechanical properties. It is also demonstrated that the tensile properties of the foams and the uniformity of cell size distribution is improved when the foam is blown with an optimized mixture of $CaCO_3$ and pre-treated TiH_2.

Keywords: Foaming Agent, Pre-treatment, Relative Density, Selective Oxidation, Stir-Casting, Tensile Properties.

1. Introduction

Metal foam is a type of cellular solids, having a combination of properties such as high stiffness with very low density and a capability to absorb impact energy. These unique combinations of properties indicate various potential applications such as packaging materials for protection sensitive devices, machinery enclosures, automobiles, and as sound absorbing material under difficult situations [2]. Mechanical testing of aluminium foams is a prerequisite for any application. The study of compressive and impact properties of metallic foams is necessary as its major applications are primarily load-bearing and energy absorption [11]. The compressive stress-strain diagram of metal foam as defined by Gibson and Ashby [1] consists of three distinct regions namely linear elastic region, collapse region and densification region. Fig. 1 shows a representative stress – strain curve of metal foam under compressive loading.

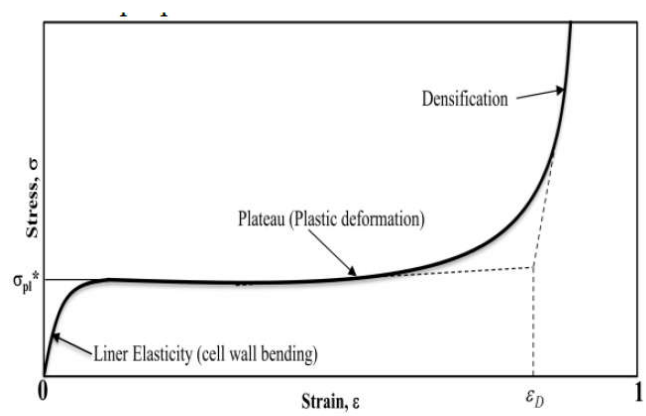


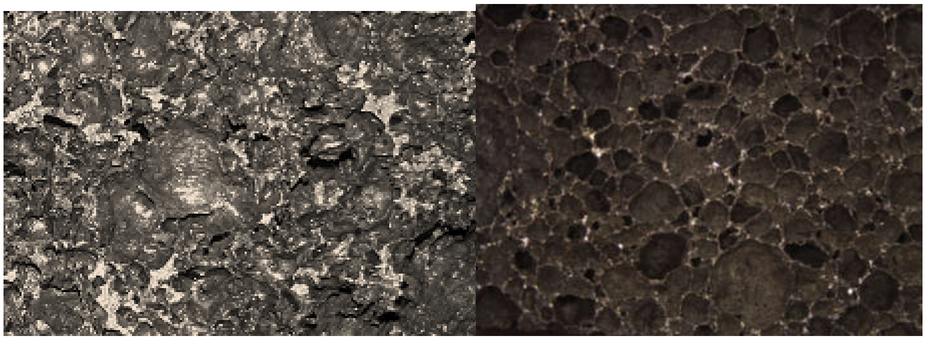
Figure 1: Stress strain curve (compressive) for metal foams [1].

The first zone (linear elastic zone) is recorded up-to small strain (about 2-3%). The second zone i.e. plateau region, continues up to about 70% of strain, characterized by a small slope of the stress-strain

curve. In some cases the curve is even horizontal. In second zone collapsing of cell continues till the foam behaves like a solid material. The third zone (densification zone) shows a rapidly increasing stress, here the cell walls become pressed together and the material attains bulk-like properties [5].
The main aim of the present investigation is to determine the variations of Physical properties (Relative Density) and tensile properties (Yield, Ultimate Stress and Elastic Modulus) of produced foam with respect to the variations of the ingredients and process parameters. The results are compared with the compressive characteristics of the closed cell Aluminium Metal Matrix Composite (Al-MMC) foams developed in the laboratory so that it can be further referred for different industrial applications.

2. Synthesis of Al-MMC Foam

The material under investigation is closed cell aluminium foam, manufactured through liquid metallurgy (Stir-Casting) route in the *Foundry Laboratory of Jadavpur University, Kolkata*, using aluminium alloy (LM6: consisting of 0.1% Cu, 0.1% Mg, 0.13% Si, 0.6% Fe, 0.5% Mn, and trace amount of Zn, Pb, Sn and rest Al). The aluminium alloy used is of density (ρ_s), 2.7gm/cm^3, having compressive elastic modulus (Es) of 69 GPa and compressive yield strength (σ_s) of 120 MPa.
As the liquid metallurgy route is comparatively less costly [6], this route was followed for manufacturing of MMC Foam. The ingot was melt in a tilting resistance furnace. The formation of foam requires a high melt viscosity which is achieved by the addition of Silicon Carbide (SiC) particulate to the melt. The amount of Aluminium is 1000 gm. 5% SiC (pre-heated) are added to the melt, which also increases the mechanical strength of the foamed component. For homogeneous mixture of SiC in Al matrix, continuous stirring is required. The achieved high viscosity allows liquid Aluminium to be stable at a temperature of TiH_2- decomposition (465°C) which is much lower than the freezing temperature of liquid Aluminium.
The homogeneous Al-SiC mixture was then poured into a pre heated mould (which is fitted with a stirring arrangement having a Zirconium coated stirrer assembly) after removal of slag as much possible, 2.5% blowing agent (Titanium Hydride) was added to the mould. TiH_2 began to decompose into Ti and gaseous H_2 when heated above about 465°C. By adding titanium hydride particles to the aluminium melt, large volumes of hydrogen gas were rapidly produced, creating bubbles that leads to a closed cell foam. It was needed to stir the mould with constant speed for good foaming.
As TiH_2 is very costly, so, manufacturing of Al-SiC foam by this method was not so cost effective. The solution to this problem is the addition of Calcium Carbonate (which is very cheap in cost) in the foaming agent. So, instead of adding 2.5% TiH_2, a dual foaming agent (2% $CaCO_3$ and 0.5% – 1.0% TiH_2) was added separately and this produces same result with minimum cost. Addition of Ca in Al matrix slightly changes the mechanical properties but it was almost negligible.
The properties of metal foams depend on many morphological features, such as pore size distribution, cell wall curvature, defects, etc. [3]. Although the exact interrelationship between properties and structure is not yet sufficiently known, one usually assumes that a uniform distribution of convex pores free of defects is highly desirable. The task for the experimentalist is to produce such structures. A short look at existing foams shows that there is still much potential for development since these often tend to be irregular [4].
Thus, the foam fabricated by this method were usually non-uniform which leads to inferior mechanical properties. The reason for this can be non-adoption of TiH_2 to the melting range of the alloy to be foamed. This is avoided by pre-treatment of titanium hydride (TiH_2) in the form of 10-15 µm diameter particles by selective oxidation [10].
Pre-treatments of the TiH_2 powder were carried out isothermally at various temperatures (450, 480, 510 °C) and times (30, 60, 120 and 180 min) under air in a chamber furnace. For heating, the ceramic crucible (with required amount of TiH_2) was placed into a volume chamber muffle furnace and was left there for the time specified. After pre-treatment all powders were gently homogenized by tumbling in a container. Hydrogen starts to be released from TiH_2 at about 405 – 470 °C with some variations between powders of different origin. However, most of TiH_2 powder starts decomposing at 465°C. As heating was carried out under air, there was a growth of an oxide layer which is roughly 100 nm thick after 180 min at 480°C and contains an outer shell of TiO_2 and an inner shell of Ti_3O.



(a) (b)

Figure. 2: Sample section: (a) using untreated TiH_2, (b) using Pre-treated (480˚C, 60 mins) TiH_2(5X)

Pre-treatment under air also reduces the amount of hydrogen and shifts the temperature of decomposition by 160°C. Using pre-treated TiH_2 for foaming Al alloys delays foaming and leads to a more uniform distribution of rounder pores. The best parameters found are close to 60 min at 480°C. It is noted that at higher pre-treating temperature (510°C), the amount of available hydrogen is not sufficient to produce uniform foam (Fig. 2).

3. Density of Al-MMC Foam

3.1 Determination of directional variation of density

In order to determine the directional variation in density, two rectangular specimens of sizes 20 x 20 x 100 mm, one with height in oriented in the direction of foaming and another with height in oriented in the lateral direction, are cut from the foamed bulk material. Figure 3 shows the reference system used. Z axis represents the direction of foaming and x and y axis represents lateral directions. Each specimen is then further cut into five pieces of size 20 x 20 x 20 mm and their densities are measured.

An uneven density distribution, within the specimen cross-section, is evident in Figure 4. Specimens with height aligned along the z-direction (i.e. in the direction of foaming) are nonhomogeneous (maximum variation of density of 33.6%), with the variations of density that have an approximate step distribution (Figure 4).

The decrease in density towards the foaming direction can be explained from the physics of the foaming process. During the foaming of the melt, as liquid metal drains due to gravity, and the solidification front moves downward, this results in decrease in density in the material. At the bottom of the foam a solidification front moves upward. At the same time, liquid metal drains towards this front, and accumulates above it before being frozen itself. Therefore the density at the bottom of the foam increases.

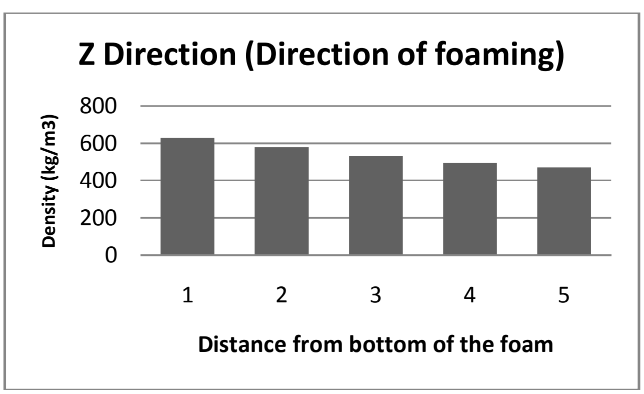


Figure 3: Variation of density of the aluminium foam in the z-direction (foaming direction), Average density = 540.2 kg/m^3

The density distributions in specimens aligned in the y-direction /x-direction are relatively uniform (maximum variation of 11.3%) as shown in Figure 3. This variation of density in the lateral direction is because of the variability of the structure of the specimen or presence on some large pores in the specimen which results in lesser density.

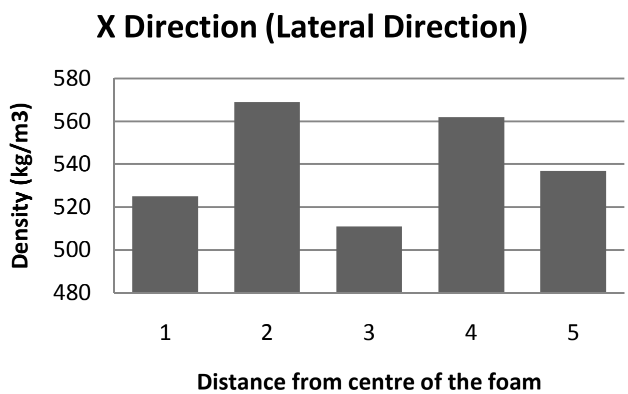


Figure 4: Variation of density of the aluminium foam in lateral direction,Average density = 540.8 kg/m^3

3.2 Effect of the production parameters on average density

Keeping in mind the objectives of the research work, some initial experiments are conducted to synthesize aluminium foam of varying density, through the variation of process parameters like percentage of foaming agents (TiH_2 and $CaCO_3$), and thickening agent (SiC). The primary foaming agent (TiH_2) are heat treated prior to application. The effect of heat treatment has noticeable impact on all the properties, including the density of the produced foam. The results are presented graphically. The results of these investigations would be useful in the synthesis of quality aluminium foams of required relative density at competitive rates.

Effects of SiC addition on the average density: During the production of aluminium foam, SiC addition was varied by 3, 5, 10, 15, and 20 % of mass of aluminium alloy used, while keeping other production parameter constant. The results shows marginal decrease in density when SiC % is increased from 3 to 5 %, further increase of SiC % did not significantly affect the density of the material (Figure 5).

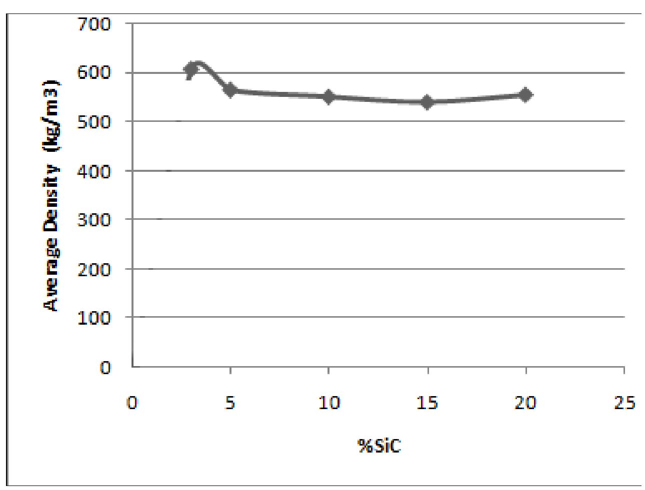


Figure 5: Effect of mass % SiC added, on the average density of aluminium foam

Effects of $CaCO_3$addition on the average density: $CaCO_3$ acts as viscosity enhancer (thickening agent) and also as a foaming agent. However amount of $CaCO_3$ added must be carefully chosen. Experience showed that if the amount of $CaCO_3$ exceeds 5% of the mass of aluminium alloy used, then in most cases, it completely oxidizes the melt as it acts as a strong oxidizer at elevated temperature [8]. Some experiments were carried out varying the mass % $CaCO_3$ addition while keeping the TiH_2 addition of 0.5% constant. It was observed that by increasing the percentage of $CaCO_3$ in the melt, density of the foam decreases (Figure 6). But above 3.5%, the decrease in the density is very marginal.

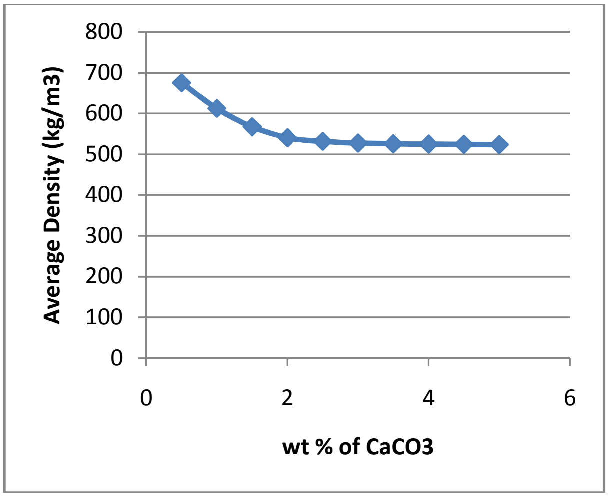


Figure 6: Effect of % $CaCO_3$ added, on the average density of aluminium foam

Effect of TiH_2addition on the average density: Percentage of TiH_2 significantly influences the density of the metallic foam. It has been observed that by increasing the amount of TiH_2 (mass % of aluminium alloy used) in the melt, density of the foamed block decreases. But when the amount of TiH_2 was increased above 2.0%, there was very marginal decrease in the density, as is shown in Figure 7. This signifies that above a critical amount of foaming agent, the density attains almost a stable value.

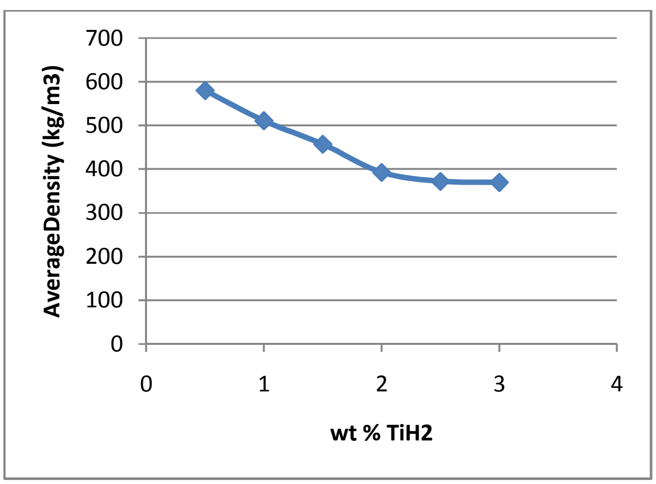


Figure 7: Effect of mass % TiH_2 added, on the average density of aluminium foam

3.3 Effects of both TiH_2 and $CaCO_3$ together acting as dual foaming agent

Some experimental investigations were also carried out to find the advantage of adding dual foaming agent. Experiments were carried out with TiH_2 as the only foaming agent. Another set of experiment was carried out with both $CaCO_3$ and TiH_2. During all the experiments 5% SiC of mass of aluminium alloy used was kept constant. It was observed that to obtain similar density without addition of $CaCO_3$ required higher amount of TiH_2, as plotted in figure 8. Therefore it is evident that similar level of density can be obtained even with lesser use of TiH_2, by use of $CaCO_3$ as secondary foaming agent.

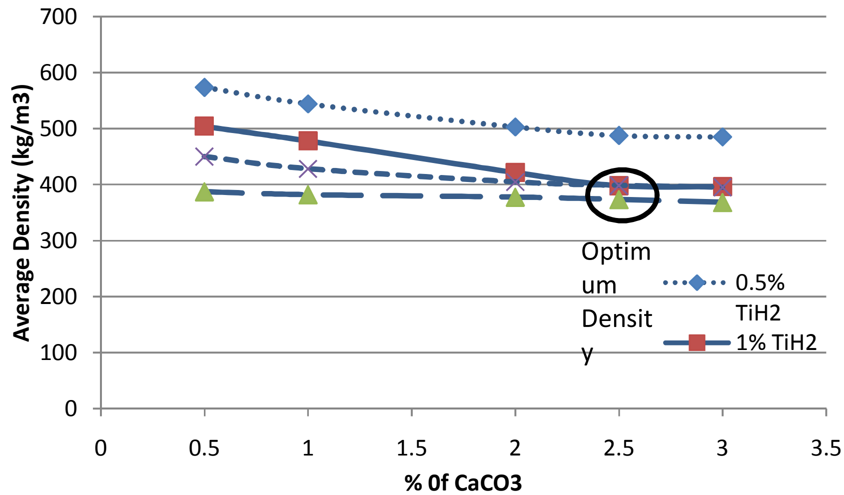


Figure 8: Effect of variation of both TiH_2 and $CaCO_3$ on average density of aluminium foam

One of the principle aims of this research is to produce low cost, low density aluminium foams. This aim has been realized to a certain extent as it has been possible to produce low density closed cell aluminium foam by reducing the use of costly TiH_2. So, as the optimum density is concerned, taking the cost into account, foaming agent comprising of 1% TiH_2 with 2.5% $CaCO_3$ is selected for best quality low cost aluminium foam.

3.4 Effects of pre-treatment of TiH2

Pre-treatments of TiH_2 under air (as described in section 2) were carried out for five sets of Temperature and each for 4 sets of time span. The treated TiH_2 in different weight% was then added to the Al-SiC melt along with fixed 2.5% $CaCO_3$. The data obtained were plotted in Figures 9 and 10. It is clear from Figure 9 and 10 that the optimum heat treatment of TiH_2 to obtain minimum density with less amount of TiH_2 used is 480˚C and the optimum heat treatment duration is 60 minutes. At very low pre-treatment temperature (420˚C) and at a high pre-treatment temperature (above 510˚C) the density is high enough. So, during the characterization of Aluminium foam samples, the pre-treatment temperature is varied from 450˚C to 510˚C for 60 minutes only.

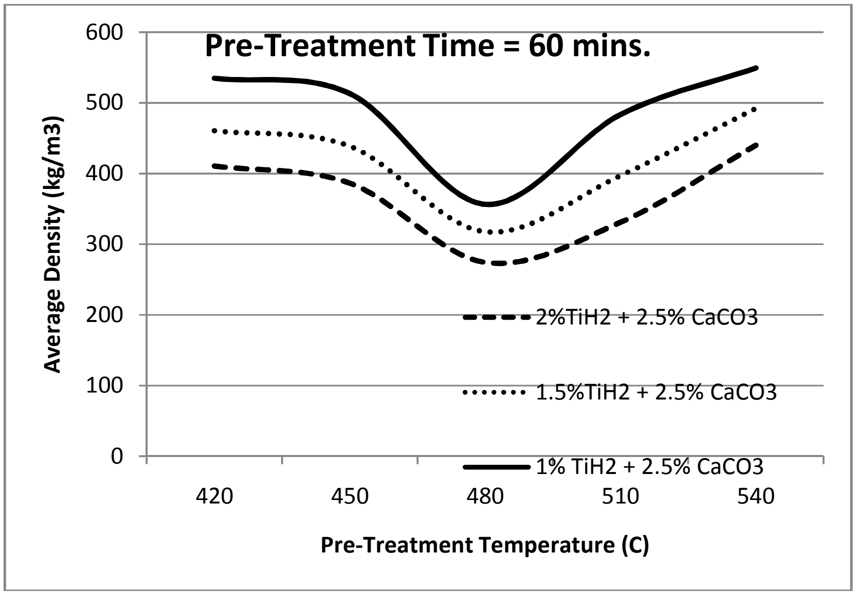


Figure 9: Variation of density with varying pre-treatment temperature of TiH_2

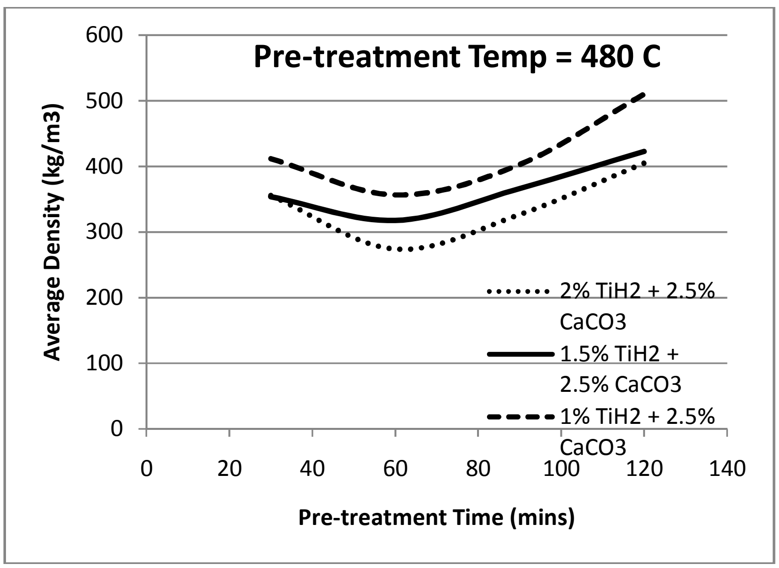


Figure 10: Variation of density with varying pre-treatment time of TiH_2

3.5 Uniaxial tensile tests

The mechanical properties of aluminium foam are yet to be characterized [7]. Aluminium foam exhibits all tensile tests are carried out on a displacement-controlled Universal Testing Machine at room temperature. The crosshead speed was 0.5 mm/min, which corresponds to a mean strain rate of about 0.1 s^{-1}. The specimens for tensile testing are Aluminium foam cubes of different Relative Density fastened with a pair of MS handle (Figure 11).

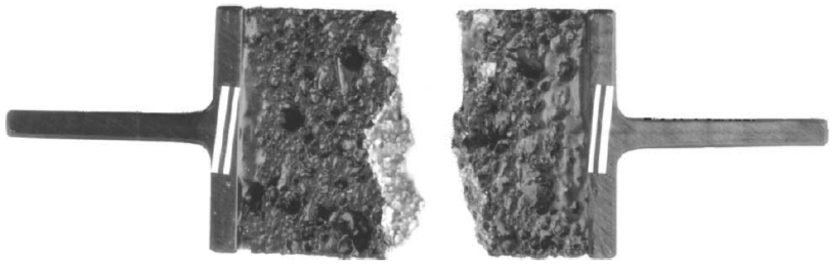


Figure 11: Tensile test specimen after failure.

Unlike compression, the Tensilebehaviour of all kind of aluminium foam shows a very brittle nature [9, 12]. Tensile behaviour of aluminium foam made by dual foaming agent ($CaCO_3$ and TiH_2 in untreated condition) of three different Relative Densities (RD) are studied. The comparison of tensile behaviour of foams made by 'untreated' TiH_2 and 'treated' TiH_2 at different temperatures are also studied.

The results of tensile tests are plotted in Figure 12. A closer look at the deformation behaviour of the foam reveals some differences. The tensile stress–strain behaviour of metal foams differs from that in compression. There is only a very small linear elastic part in the stress–strain curve followed by a large plastic part. In plastic regime of the stress–strain curve, the deformation has a very inhomogeneous distribution.

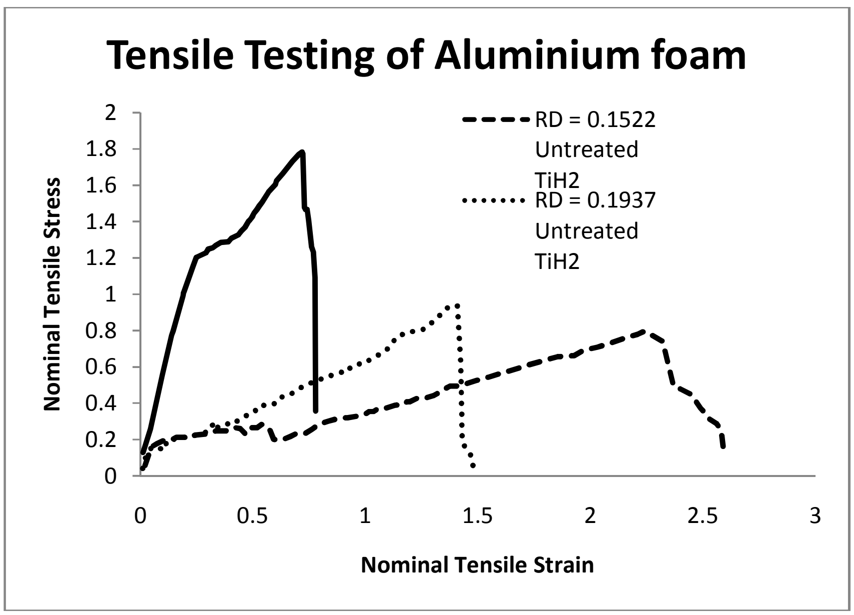


Figure 12: Tensile stress (MPa) -strain curves of aluminium foam

It is also noted that the elastic modulus decreases with increasing deformation for each curve. This happens slowly at first and then it decreases more significantly after reaching the peak stress. The tensile properties of the produced aluminium foam are analysed. In comparison with compressive elastic moduli of aluminium foams the tensile elastic moduli seems to be higher.

The similar experiments were repeated for foam samples fabricated after the heat treatment of TiH_2. The results of tensile tests were plotted in Figure 13.

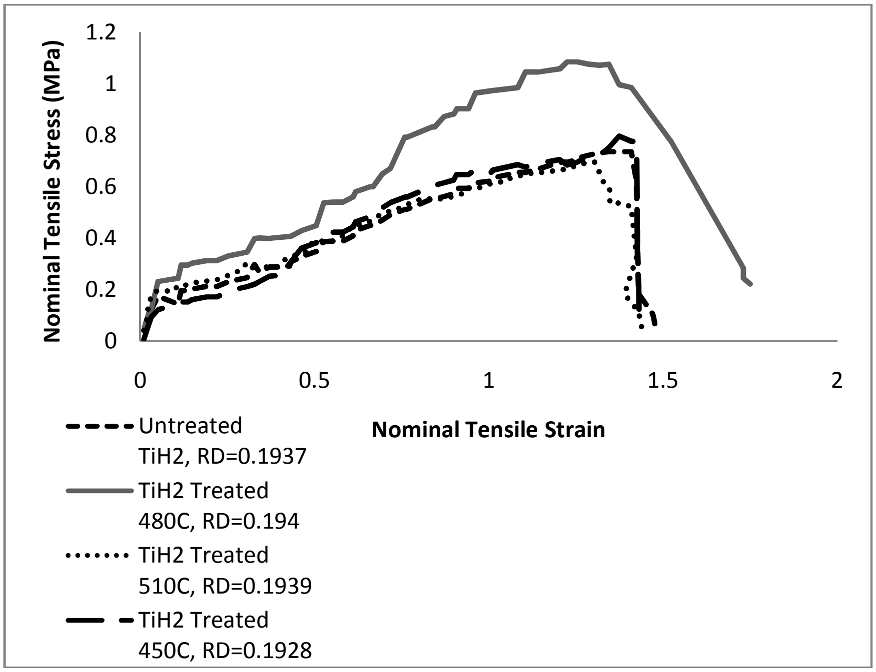


Figure 13: Tensile stress-strain curves of aluminium foam made by treated TiH_2

It is further noted that the elastic modulus decreases with increasing deformation for all the samples. Although, the samples are of almost same RD value, but due to the presence of homogeneous structure, the sample made from TiH_2 treated at 480 ˚C for 60 minutes, results with more Yield and Ultimate Tensile Strength. Therefore, the thermal treatment of TiH_2 is optimized at 480 ˚C for 60 minutes, as this treatment produces best results. Similar results were obtained for compressive behaviour and electrical behaviour also [13, 14]

4 Conclusions

Determination of Relative Density and Uniaxial tensile tests are carried out find the tensile properties of Al- MMC foam. The cost of production can also be reduced if the foaming agent(s) are pre-treated by selective oxidation to produce delayed gas generation. It is possible to produce aluminium foam of required average relative density by controlling production parameters. The non-homogeneity of pores is another limitation which can be reduced to almost nil by controlled heat treating of the metal hydrides.

While subjected to uniaxial tensile forces, there is only a very small linear elastic part in the stress–strain curve followed by a large plastic part. In plastic regime of the stress–strain curve, the deformation has a very inhomogeneous distribution. The tensile elastic modulus is higher than the compressive elastic modulus, and can increase even more by selective oxidation by pre-treatment of a foaming agent (TiH_2) to 480℃ for 60 minutes. Such findings will be very much essential in order to proper design and application of this developed material.

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