FOUNDRY

A356 Alloy Foaming by Titanium Hydride[1]

Zohair Sarajan*

Department of Materials Science and Engineering, Yazd Branch, Islamic Azad University, Yazd, Iran Safaeeyeh
*e-mail: zohairsarajan@iauyazd.ac.ir, zohairsarajan@yahoo.com

Abstract—In this study the parameters which affecting on foaming process of aluminum A356 for preparing of light products are investigated. Titanium hydride (TiH_2) powder as a foaming agent (0.5 to 2.5 wt %) added to the aluminum melt. This is focused on thermal decomposition behavior of titanium hydride on the melt foaming during casting and unidirectional solidification of A356 alloy. Therefore, the effects of heating temperature, stirring time and TiH_2 wt %, on percentage of porosity have been investigated. It was found that with the optimum torque of 0.35 Nm for the melt and TiH_2 addition of 1.0−1.5 wt %, remarkably foaming efficiency could be achieved. Foamed A356 cross sections were microscopically characterized by Scanning Electron Microscopy corresponding to different TiH_2 contents. The optimum amount of titanium hydride content induces uniformity in porosity cell structure distribution in the whole cross section of the foamed aluminum. Medium thickness of thin cell wall is near to 20 μm which is easily broken or disrupted.

Keywords: SEM characterization, TiH_2, A356 composite, foamed structure, density

INTRODUCTION

Syntactic foams are especially beneficial under compressive loading conditions because particles become load bearing elements under compression. Syntactic foams show a large stress plateau under compression, which corresponds to the densification of the material and results in high energy absorption [1−3]. Heat treating of TiH_2 in air to temperatures between roughly 400 and 500°C has been reported to delay the decomposition of TiH_2 and it was found to be effective when adding TiH_2 to molten metals. In recent years, there has been a growing demand for the use of metal foams, especially aluminum and its alloy for automotive, railway, and aerospace applications where weight reduction and improvement in safety are considered. For a successful usage of closed cell aluminum foams in load-carrying, applications such as sandwich panels, knowledge of tensile, fracture, and fatigue properties are important [4]. Aluminum alloys A356 is the most widely used and studied aluminum–silicon casting alloys. This alloy consist of aluminum with 6.5–7.5% silicon and 0.20–0.45% magnesium. The lower amount of iron reduces the formation of Al−Fe intermetallics, which have a detrimental effect on mechanical properties [5−7]. The as-cast microstructure of these alloys consists primarily of dendrites of α-aluminum containing silicon and magnesium in solid solution, surrounded by eutectic aluminum–silicon. The Al−Si eutectic takes the form of coarse platelets, unless a modifier such as strontium, sodium,

or antimony is added [8, 9]. Research in the past focused only on the mechanics and energy absorption of aluminum foam material and rarely on the acoustics properties of aluminum foam especially sound insulation property in Al−Si closed-cell aluminum. Because of its special structure, aluminum foam has a great potential application in fields such as sound insulation and noise reduction [10, 11]. Titanium hydride is decomposed at about 465°C, which is below the melting point of Al−Si (570−615°C) and, this alloy is formulated according to the following chemical reaction $TiH_2(s) \rightarrow Ti(s) + H_2(g)$. It has been shown, for example, that compression strength is connected to the density of foam, thus allowing this property to be adjusting within a certain range. However, as density cannot always be varied freely and in order to gain more control over the properties of metallic foams, adjustment of other variables seems desirable including alloy composition, foam morphology (size and shape of cells) and the metallurgical state of the matrix metal. During Al−Si alloy melt foaming process, especially in the cooling stage, the pores were elongated [12−16]. The most popular alloy is A356. These alloys are featured with excellent casting characteristics, heat-treatable, weldability, and pressure tightness. The main goal of this study is to investigate the influences of titanium hydride content as a foaming agent and holding temperature on porosity percentage, size and cell structure uniformity of the foamed A356 alloy. Uniformity throughout the length with respect to the porosity are important and need further study and are beyond the scope of this work.

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[1] The article is published in the original.

EXPERIMENTAL PROCEDURE

This work is an experimental procedure in which A356 alloy is used for the matrix material. Firstly, it is melted one kg of this alloy in Al_2O_3 coated steel crucible under argon atmosphere. Liquidus temperature of the A356 alloy used in this study is 625°C. The liquidus temperature of this hypoeutectic alloy was calculated by Pro-Cast software based on chemical composition. By using this software, it is possible to predict the liquidus temperature of both hypo and hypereutectic of aluminum alloys, based on their chemical compositions. Chemical composition of the material is shown in table. Secondly, it is added of aluminum powder (6 wt %, the purity of Al > 99.98 wt % with 55 μm in diameter) as the adjuster into the melt by the impellor with a constant stirring speed of 450 rpm to raise the viscosity of the melt. The viscosity of the aluminum melt was measured by monitoring the torque moment of the paddle axle.

Uniform distribution of the foaming agent in the base metal and to improve the consistency of the foam, mechanical stirring was instituted. This was accomplished by using as a stirrer a disk of stainless steel, 2 inches in diameter, cut at the radius in 4 or 5 places with the blades bent so that they formed a multibladed fan. The stirring unit was mounted at the end of an 18-inch-long, 3.8-inch-diameter rod driven by the stirrer motor operating at 400−1200 rpm. The next step is the addition of titanium hydride powder (purity >99 wt %, ∅40 μm) as the blowing agent. When the stirring torque of the melt reaches 0.35 Nm, the titanium hydride powder (0.5 to 2.0 wt %) is added and dispersed into the melt. Three minutes after the impeller stirring reaches the speed of 1200 rpm, titanium hydride powder acts as a foaming agent and the melt is gradually foamed. The optimum stirring parameters according to the results are, stirring speed of 1200 rpm, holding temperature of 575°C and melt stirring torque of 0.35 Nm. Melts are held in the furnace at 575°C to allow the blowing agent to completely decompose. At this stage, bubbles in the melt continuously grow with time and a melt with a cellular structure is formed. The liquid metal was stirred under a hot argon atmosphere at about 90°C and the maximum flow of 2150 cm^3/min. Argon was directly injected inside the

Chemical Composition of A356 alloy

Alloying elements, wt %							
Si	Cu	Zn	Fe	Mg	Ti	Mn	Al
7.00	0.2 max	0.1 max	0.2 max	0.45	0.2 max	0.1 max	balance

melt to control the oxidation during the foaming process. This controlled atmosphere decreases magnesium loss to the minimum. However, the loss of Magnesium in the alloy was equalized by Al-10 wt % Mg hardener alloy before the addition of titanium hydride as the blowing agent. This time interval is defined as holding foaming stage whose duration is defined as holding time.

Simple-shaped foamed A356 parts could be manufactured by investment casting molds, using a special mold design and filling the mold inside a hot furnace. Foamed parts obtained by this method have a surface skin. Thus they can be used, for example, as foamed cores embedded in aluminum parts. For the manufacturing process, the ceramic mold could be attached to the ceramic crucible cover by an extension in the mold. This extension is open to the mold and uses as "mold entrance opening." The crucible and the ceramic mold are placed in the furnace and heated simultaneously. When the melt attains the desired temperature of 575°C, the temperature of the mold is about the same. After the foaming process, the crucible is filled up with the foam, and then the mold is gradually filled. When the mold sprue is filled with the foam, the stirring of the impeller could be stopped. An extra time is then allowed to insure that the filling is complete. Finally, the mold could be removed from the melting furnace and the foam inside the mold is allowed to solidify.

The experimental setup is shown in Fig. 1. Foams produced by this technique exhibit a closed porosity. The density, ρ^*, of the foamed specimen is measured by Archimedean rule. The relative density is defined as ρ^*/ρ_s, where ρ_s is the density of the matrix of which it is made. The porosity is one of the most important parameters of metal foams. Bulk porosity (Pr_b) refers
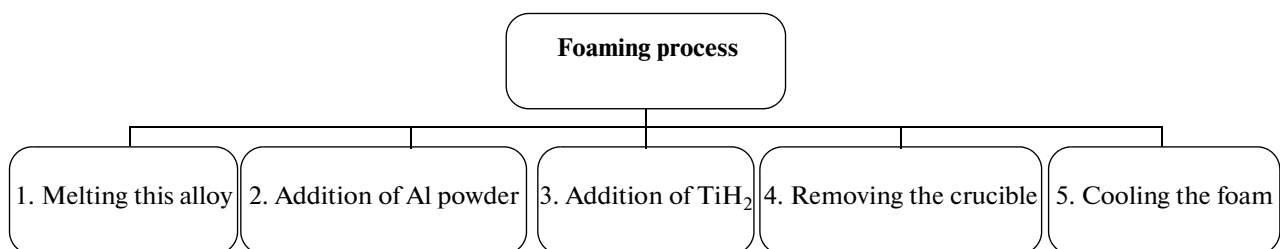

Foaming process

1. Melting this alloy | 2. Addition of Al powder | 3. Addition of TiH$_2$ | 4. Removing the crucible | 5. Cooling the foam

Fig. 1. The experimental setup for foaming process of A356.
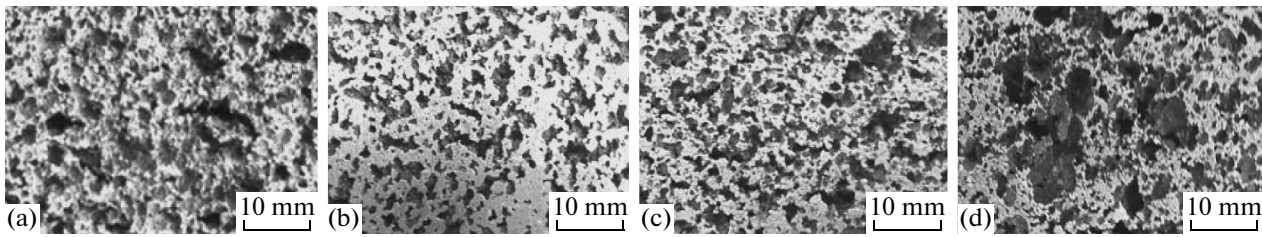
Fig. 2. Cross section of A356 foam corresponding to different stirring time t_s (after foaming with titanium hydride: 1.0 wt %, 50 μm). The stirring time for the samples a–d is 60, 90, 120 and 150 s, respectively.

to the volume fraction of all the pores in a finished product of the A356 alloy foam. It is usually calculated from the weight W and the volume V_s, where V_i is pore volume, V volume of a sample, and ρ is the specific weight of the matrix. It is recommended that thermo gravimetric analysis should be used to study hydrogen release in the temperature range of 25 to 1000°C to determine the efficiency of the hydrogen gas releasing and then to compare it with its theoretical volume. The morphology of pore cell structure and microstructure is characterized by the optical and Electron Microscopy.

RESULTS AND DISCUSSION

During the stirring foaming stage, the pore structure of A356 melt foam varies with stirring time and can be measured by using the instant freezing and the scanning mentioned in the previous section. Figure 2 shows the cross sections of A356 foam corresponding to different stirring time t_s. The stirring time for the samples a–d is 60, 90, 120 and 150 s, respectively. It shows that the number of pores on the cross sections is a close relationship of stirring time t_s (Fig. 3).
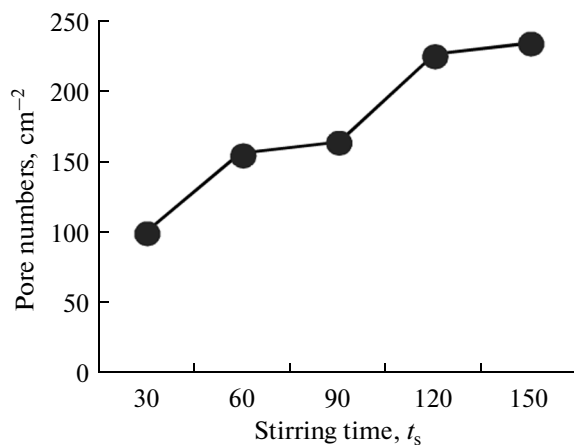
It also indicates that during the stirring period of 60–150 s, the number of pores in A356 foams is increased as a function of the stirring time, but the size of pores decreased. This can be explained by the fact that when the titanium hydride is added to the thickened melt by vigorous stirring, it starts to release large amounts of hydrogen and a large number of bubbles are formed in the melt. The impellor with high revolution speed will make the bubbles smaller, and simultaneously a considerable proportion of hydrogen is expelled out from the melt to the atmosphere. Finally, the released hydrogen from the decomposition of titanium hydride remains in the melt and the hydrogen escaping from the melt is in an approximate balance. This causes the porosity of A356 melt foam to remain constant while the pores number increases and the pore diameter decreases during the stirring foaming period.

Figure 2 depicts the effects of stirring time t_s on pores number. According to the experimental points shown in this figure, porosity of A356 melt foam can be extrapolated immediately after the stirring period required for foaming. The result indicates that the number of pores in A356 foam with stirring time t_s of 60 to 150 s is 120 to 220 per unit area (cm^{-2}) (Fig. 3). It also shows that during the stirring foaming period from 60 to 90 s, the porosity of A356 foam is kept almost constant. Besides, the number of pores will increase until the time reaches about 120 s. There is a nonuniform cell structure especially in Fig. 2c which is explained by TiH$_2$ decomposition into titanium and hydrogen at this range of temperature. Sufficient foaming kinetics occurs and hydrogen releasing is accelerated which causes very rapid bubble coalescence. The final bubble size and total porosity volume are directly related to hydrogen gas content in the melt. This is because of titanium hydride decomposition and growth rate between bubble and liquid-solid interface.

Porosity content as a function of holding temperature shows that optimum temperature is between 545 to 615°C for A356. The vertical cross section of the foamed aluminum samples at different holding temperatures is shown in Fig. 4. This figure exhibits cell structure variations in foamed A356 and shows that at different temperatures the pore size has been varied,
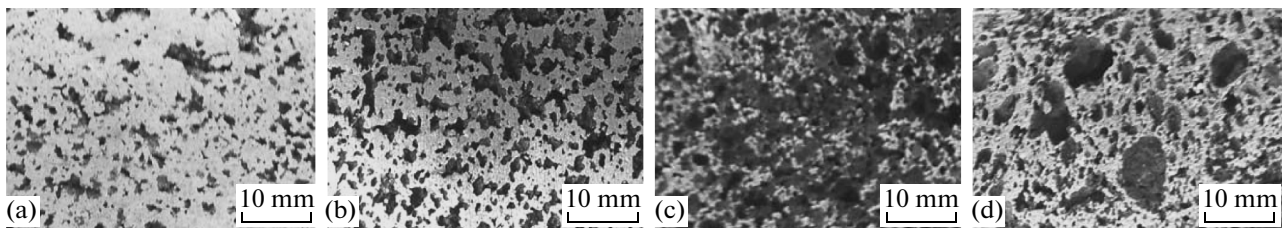

Fig. 3. Effects of stirring time t_s on pore number, per unite area (cm^{-2}) (titanium hydride: 1.0 wt %, 50 μm). The stirring time for the samples a–d is 60, 90, 120 and 150 s, respectively. It is illustrated that the number of pores on the cross sections has a close relationship with stirring time t_s.

Fig. 4. Cross section of A356 foam corresponding to different holding temperature. (after foaming with titanium hydride: 1.0 wt %, 50 μm). (a) 545°C (b) 565°C (c) 595°C (d) 615°C.
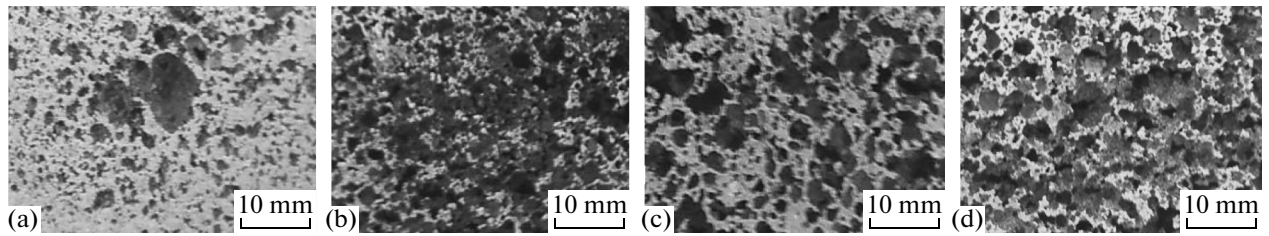

Fig. 5. Cross section of A356 foam corresponding to different TiH$_2$ content. (after foaming at holding temperature of 595°C). Titanium hydride: (a) 0.5% (b) 1.0% (c) 1.5% (d) 2.0%.

and there are also a few bubble zones at the bottom. As illustrated, at the temperature of 565°C, there is a uniform cell structure which is explained by favorite TiH$_2$ decomposition into titanium and hydrogen at this temperature. Solidification range in A356 alloy is a major factor in sufficient foaming kinetics and accelerates hydrogen release which causes bubble coalescence very rapidly and uniformly.

Figure 5 shows that the addition of 0.5 wt % TiH$_2$ is insufficient. Nonuniform irregular porosity cell structure is shown in Fig. 5a. The addition of 1.0 to 1.5 wt % TiH$_2$ induced a wide range of uniformity of spherical porosity cell structure distribution. As it is shown in Fig. 5d, the addition of 2 wt % TiH$_2$ induced nonuniform porosity cell structure, but the released hydrogen gas was completely absorbed by the melt and largely increased the foamed aluminum volume.

However, the maximum extent of the volume is limited. Figure 5b illustrates a high uniformity of spherical porosity cell structure distribution, and Fig. 6 shows the relationship between density of the foamed A356 and TiH$_2$ content at the holding temperature of 565°C. As shown in Fig. 6, the porosity of the foamed A356 with the addition of 1.0 wt % TiH$_2$ has remarkably increased. The addition of 1.0 to 1.5 wt % TiH$_2$ induced a wide range of uniformity of spherical porosity cell structure distribution in addition to favorable decrease in bulk density. Figure 7 shows the SEM micrograph of the foamed A356 cross section corresponding to different TiH$_2$ contents. As shown, medium thickness of thin cell wall is near 20 μm which has easily been broken or disrupted. These thin cell walls are formed by the excessive foaming. These experimental results indicate that the optimum content of TiH$_2$ and more hydrogen gas release increase the porosity volume and foaming efficiency. As hydrogen gas release is increased, it escapes through the melt and may result in diminished the foaming efficiency. Therefore, the optimum amount of titanium hydride content is 1.0−1.5 wt % that induces uniformity in porosity cell structure distribution in the whole cross section of the foamed aluminum.

A low viscosity tends to drain the liquid and cause the hydrogen gas to escape before the foaming, which leads to structural unsoundness of the foam with a lower porosity. Under this condition, there is a bubble-free zone at the bottom because of the surface tension of the melt causing the liquid to flow out of the foam.
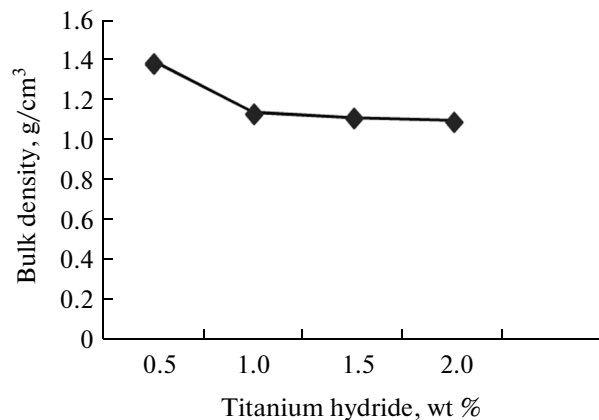

Fig. 6. Density as a function of TiH$_2$ content in A356 (after foaming at holding temperature of 565°C). The porosity of foamed specimen with the addition of 1.0 wt % TiH$_2$ has been remarkably increased.
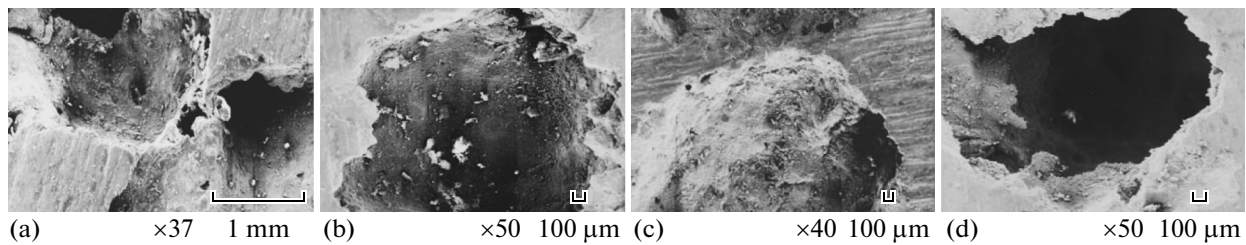
Fig. 7. SEM micrographs of foamed A356 cross section corresponding to different TiH$_2$ content. (after foaming at holding temperature of 565°C). Titanium hydride: (a) 0.5% (b) 1.0% (c) 1.5% (d) 2.0%. Medium thickness of thin cell wall is near to 20 μm which is easily broken or disrupted. The optimum amount of titanium hydride content is 1.0−1.5 wt % that induces uniformity in porosity cell structure distribution in the whole cross section of the foamed aluminum.

Contrarily, the higher viscosity could slow down the drainage process and therefore assist in the retention of bubbles, which results in the production of foam with a higher porosity.

Therefore, melt with a sufficient viscosity is important for stabilization of the liquid foam. The hydrogen gas causes the melt to expand, whereby the internal gas pressure, P_{H_2}, becomes sufficiently large to overcome the external forces. The external forces are the pressure in the bubble resulting from the bubble-melt interfacial energy, P_C, and the ambient pressure, P_A. The expression for the continuous growth of the hydrogen bubble in the melt is given by following Eq.

$$p_{H_2} \geq P_A + P_C$$

where $P_C = 2\sigma/r$ (σ is the surface tension of the melt; r is the radius of the bubble). Therefore, the pressure is inversely proportional to of the bubble radius, thus the smaller the bubble, the larger the pressure in the bubbles will be. Assuming the radius of the bubble to be 0.05 mm, the pressure for bubble formation in the A356 melt is about 178 atmospheres. Hence, a very high pressure is required for the homogeneous nucleation of a smaller bubble. In practice, such a pressure is not attainable in the melt. However, many bubbles form in the melt, thus indicating that the barrier for nucleation is easily surmounted. This implies that effective heterogeneous nuclei are present. However, TiH$_2$ powder is capable of wetting the melt and reacting very quickly after it comes into contact with the melt which causes the supersaturated hydrogen in the liquid. Hydrogen bubbles adhere to the surface of residual TiH$_2$ particles and act as centers of nucleation during the decomposition reaction of the TiH$_2$. Eventually, a major part of the hydrogen bubble is released and escapes from the liquid at the free surface with the continuous reaction of TiH$_2$ particles. The larger pore forms may be due to the sufficient diffusion of saturated hydrogen in the melt. The degree of hydrogen diffusion from the surrounding liquid strongly depends on the solidification rate. The formation of small roughly spherical pores first occurs from the nucleation of hydrogen bubbles at the solid-liquid interface.

Such a closed cell structure in A356 foams is of interest in weight sensitive structural applications. In this kind of applications where a certain level of modulus and strength are required for load bearing capacity, the foams present an option to replace higher density materials. If it leads to development of foams with high mechanical properties at low density, then the weight savings in load bearing structural applications can be realized. Use of A356 foams in structural applications is difficult, unless they are present in the form of sandwich structures. These low strength foams may be suitable for applications related to energy absorption under compression, vibration damping, and core materials in sandwich structures.

CONCLUSIONS

Thermal decomposition behavior of titanium hydride is the main mechanism for the melt foaming and consequently providing uniform porous structure in the solidified castings. Properly controlled viscosity and solidification of the melt promote good uniformity of the pore structure of the A356 foams. Porosity percentage and the pores size are function of TiH$_2$ wt %, because the released hydrogen gas is completely absorbed by the melt and largely increases the foamed A356 volume. The effect of viscosity and the cooling conditions on the foam ability of the molten A356 alloy was investigated using the unidirectional solidification method. Increase in the stirring period causes the number of pores being increased and the size of pores to be decreased. The existence of the aluminum powder in the melt is necessary for viscosity controlling of the melt. At the temperature of 565°C there is a uniform cell structure. The porosity of foamed A356 with TiH$_2$ addition of 1.0 wt % has been remarkably increased, and 1.0 to 1.5 wt % provided a high uniformity of spherical porosity cell structure distribution besides having a favorable decrease in bulk density.

ACKNOWLEDGMENTS

Study on A356 Alloy Foaming Fabrication by Melting method Using Titanium Hydride) for the support of this work.

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