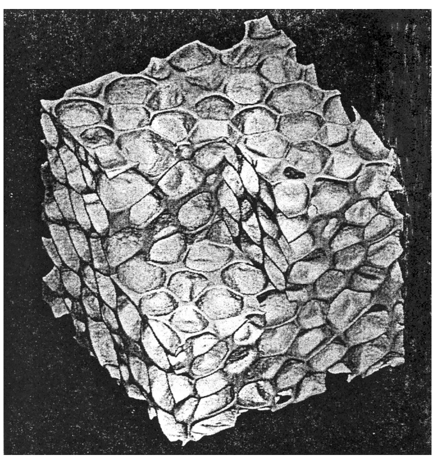
Metal Foams

Jason Fisk
College of Science, Engineering and Technology
Marian Shih, Faculty Nominator



Introduction

The worlds of physics and chemistry have once again come together to discover a new product and determine many beneficial uses for the material. It took researchers in the chemistry field to create the product and physicists to determine the unique properties that it had. The new material they have created is metal foam.

Foams are generally thought of as being a mixture of liquid and gas, but in this case the foams consist of solid and gas. The foams are naturally stiff due to their metal composition, but they are also very lightweight due to the fact that they are foam and have a very low density compared to their solid counterpart. Their unique property of being lightweight yet stiff has led researchers to dream of many different applications for which they could be used. The metal foams show promising potential in the automotive, aerospace, nautical, railway, building, civil engineering, and medical industries, just to name a few.[1]

Thus, the areas of research for metal foam seem to be endless. Every day scientists are coming up with new characteristics of the foam that need to be examined. They have found that the process for creating the foam seems to impact heavily the quality of the final product, so researchers have spent many hours trying to come up with new ways of producing the metal foam to enhance its already attractive qualities. Many other foams have been used as sound absorbers, so research has been performed to see if metal foam can do the same. Foam has also been used as thermal insulation in past applications; thus a lot of work has been done to see if the stiff metal foam could be used for thermal insulation in many building applications. Researchers have made many encouraging discoveries over the years pertaining to metal foam and some of their key conclusions are summarized in this report.

Processes for Creating Metal Foam

A great deal of research involving the creation and production of metal foam has been ongoing. This is partly because different processes cause the foam to have different properties. There are many different processes for producing metal foam, and each one seems to have advantages and disadvantages compared with the others. Today one of the most common types of foaming processes is the compact-powder foaming process, a process that consists of five different stages: making the precursor, initial pore formation, pore inflation, foam degradation, and solidification.[1]

The first stage in the compact-powder foaming process, making the precursor, consists of mixing the metal powder that is going to be foamed with an appropriate blowing agent. The metal powder and blowing agent are mixed and then compacted into a dense material called the precursor.[1] The most common type of metal used in this process is aluminum, but other metals can be used. Other aluminum alloys and metals with similar properties to that of aluminum have been foamed using the compact-powder process. The blowing agent of choice for foaming aluminum seems to be TiH2. Other hydrides have been successfully used as blowing agents, but there seems to be no apparent benefit for using them and the titanium hydride compound is the most cost effective.[2]

Once the precursor is made, the next step in the process is the initial pore formation. This involves heating the precursor to the point that the metal in the precursor melts and becomes a liquid. At that point not only does the metal become a liquid, but the blowing agent decomposes and starts to release a gas. The gas in the case of the titanium hydride is hydrogen.[2] The points in the precursor where the hydrogen gas starts to evolve become the nuclei of the initial pores of the foam, which leads to the next stage of the development of the metal foam.[1]

The next stage of the process, pore inflation, actually started in the previous step and continues in this step. The temperature is continuously increased very cautiously. The more carefully the temperature is controlled, the better the quality of the final metal foam product. Control becomes difficult because the thermal conductivity of the precursor rapidly decreases as the foaming process takes place. While the temperature is continuously increased, the blowing agent continues to decompose, thus giving off more and more gas. The nuclei formed in the previous step continue to swell, creating the foam.[2]

Foam degradation is not really an important stage in the compact-powder foaming process, but it is worth some discussion. While the pores of the foam are being created, some of them start to degrade. Liquid begins to flow towards the bottom of the foam mixture, allowing the foam bubbles to come together. They constantly become thinner and unstable until the next and final step in the process.[1]

Once the precursor has completely become a foam-like structure, it can be solidified. The foam while in its liquid state is very unstable and needs to be cooled as quickly as possible to protect it from collapsing. The material must be cooled below the melting point of the metal used in order to stabilize the metal foam.[1]

A nice advantage of the compact-powder process is that the foam can easily be molded into various shapes and structures. There are three distinct shapes that have great possibilities in the industrial world. First, the foam can be made into sheets by rolling the precursor before heating it. The precursor can also be extruded into rods to form foamable rod-like structures. Finally, the precursor can be bonded with solid aluminum or steel sheets to form foam sandwiches.[2] All three foam structures have many useful possibilities. The following block flow diagram in Figure 1 summarizes how to make each of the three structures:

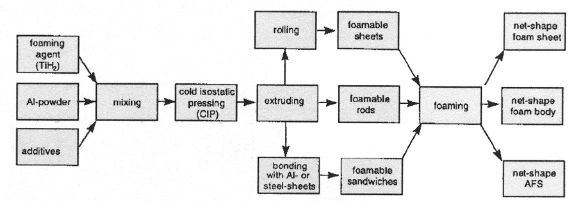


Figure 1. The Compact-Powder Process[2]

Technique for Monitoring Metal Foam Formation

In order to improve on processes for creating metal foam such as the one described above, scientists have devised techniques to monitor the formation of the foam. They know what characteristics cause the foam to have favorable properties and which ones cause the foam to be undesirable. By watching the evolution of the developing foam, the scientists might be able to prevent the foam from developing in an unfavorable way. They can see where the foam formation starts to go wrong and hopefully correct that portion of the process, thus creating a better product.

Typical methods for observing aqueous foam formation such as fluorescence or light scattering measurements are not applicable for metal foams because of their intransparent nature.[3] New methods had to be developed for watching the evolution of the metal foam. Synchrotron radioscopy is one of the most popular techniques that has been developed for such a task; it allows researchers to view the stages of metal foam development in great detail and resolution. The formation, growth and decay of the foam can be observed with the real time images created by the synchrotron radioscopy method.[3] (See Figure 2.)

The synchrotron radioscopy technique is not really all that complicated. The foam is generated in a furnace equipped with two water-cooled aluminum windows. A synchrotron x-ray beam of 33.17 keV is passed through one of the aluminum windows. The x-ray beam produces an absorption radiograph, which is captured using a CCD camera located behind the other aluminum window. The CCD camera used is 1024 x 1024 pixels with 40mm pixel size. It reads out at frequencies between 2 and 3 Hz.3 A diagram of the typical equipment layout used in this method is illustrated below in Figure 2, along with actual pictures obtained using the CCD camera from an experiment in Figure 3:

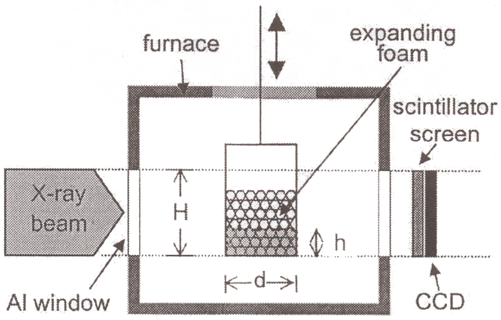


Figure 2. Equipment Layout for Synchrotron Radioscopy[3]

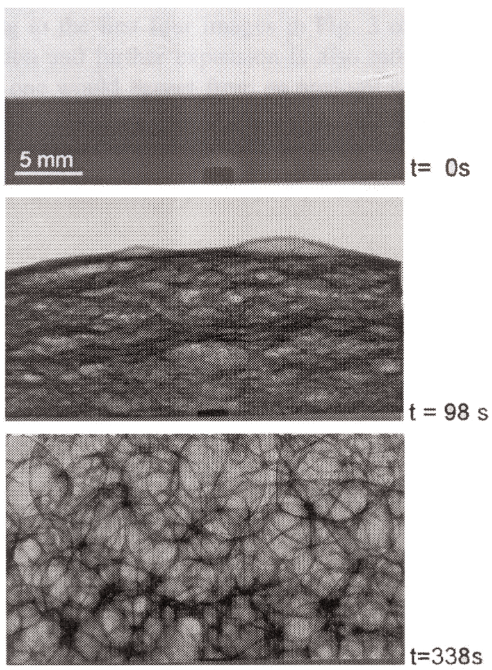


Figure 3. Images taken using synchrotron radioscopy technique, where *t* is the time from the start of the experiment

The top picture shows the material before the foaming process. The middle picture illustrates what the foam looks like upon initial formation of the pores. The bottom picture displays an image of the final product.[3]

Sound Absorption of Metal Foams

One potential application of metal foam is its use as a sound absorber. Metal foam is not only lightweight and stiff, but it has decent sound absorption properties as well. Sound absorption is not usually a property associated with metallic materials. Usually materials such as glass wool and polymer foam are thought of as good sound absorbers, but metal foam could also be put into that category. Metal foam behaves in a similar fashion to other sound absorbers, but adds the benefit of extra strength.

When examining the sound absorption properties of materials, three pieces of data are of particular interest. The first and possibly of the most interest is the sound absorption coefficient, a. The sound absorption coefficient measures the amount of energy from a sound wave absorbed by the material; it usually depends on the thickness of the material being used. The second piece of data of interest is the characteristic impedance, *Z*. The characteristic impedance is "the ratio of sound pressure to air particle velocity at the entrance surface of an unlimited medium at which a plane sound wave impinges perpendicular to the surface."[4] The last of the three important pieces of data for sound absorption is the propagation constant, *m*. The propagation constant has both a real and imaginary part. The real part describes how much of the sound will be attenuated as the sound wave travels across the medium of the foam. The imaginary part describes the speed of sound. All three pieces of data can be found experimentally.[4]

To find the characteristic impedance, *Z*, first the surface impedance immediately in front and behind the material being examined must be determined. The surface impedance in front of the material, *Zs*, can be measured using an impedance tube, and the surface impedance immediately behind the material can be found using the following equation:

$$Z_r = -(\rho_0 c_0) i \cot(\omega d / c_0) \qquad (1)$$

where ρ_0 = 1.2 kg/m^3, c_0 = 343 m/s and *d* corresponds to the depth of the impedance tube.[4] Then after the two values have been found, the characteristic impedance and the propagation constant can be found using the following equation:

$$Z_s = Z \frac{Z_r \cosh(mL) + Z \sinh(mL)}{Z_r \sinh(mL) + Z \cosh(mL)} \qquad (2)$$

Since there are two unknown variables in the above equation, two separate measurements must be taken to solve for them. After the separate experiments have been performed and data for each one tabulated, *Z* and *m* can be calculated using the following two equations:

$$Z = \pm \left\{ \frac{Z_{s1} Z_{s2} (Z_{r1} - Z_{r2}) - Z_{r1} Z_{r2} (Z_{s1} - Z_{s2})}{(Z_{r1} - Z_{r2}) - (Z_{s1} - Z_{s2})} \right\}^{\frac{1}{2}} \qquad (3)$$

and

$$m = -\frac{1}{2L} \ln\left(\frac{Z_{s1} - Z}{Z_{s1} + Z} \frac{Z_{r1} + Z}{Z_{r1} - Z} \right) \qquad (4)$$

Once *Z* and *m* have been calculated, the sound absorption coefficient can be found using the following equation:

$$\alpha = 1 - \left| \frac{Z_s - Z_0}{Z_s + Z_0} \right|^2 \qquad (5)$$

where $Z_0 = \rho_0 c_0$ is the characteristic impedance of air.[4] As stated earlier, the sound absorption coefficient usually varies depending on the thickness of the material being investigated, but using the equation above, the sound absorption coefficient of a sample of arbitrary thickness can be determined.

Generally metal foam can absorb sound without any modification made to it, but it is not considered to be a good sound absorber in its initial state. Although adjustments can be made to optimize the thickness and density of the foam to increase its sound absorbing ability, the initial metal foam cannot compete with other sound absorbing materials. Certain modifications can be made to help increase the sound absorption coefficient of the metal foam, thus helping it to compete with other materials in this category.

One modification found to help increase the sound absorption properties is rolling. Different samples of metal foam with varying thickness have been rolled to examine the effects of rolling the samples. It was found that rolling the metal foam definitely increased the sound absorption coefficient in each sample, but had greater effects in the thicker samples. The thinner samples did benefit from the rolling modification, but effects were limited compared to their thicker counterparts.[4]

Similar to the attempt at rolling the foam, metal foam samples have also been introduced to compression. The samples have been reduced to about 40% of their original thickness by compressing them either directly or progressively. It does not seem to matter whether the foam is compressed directly or progressively; the results seem to be the same. Once again the modification has been found to increase the sound absorption coefficient. The results seem to be very similar to the rolled samples. In both cases the best results were obtained when the relative density of the foam was low.[4]

The third alteration made to some metal foam samples in an attempt to increase sound absorption properties has been drilling holes in the samples. Samples of foam with low relative densities have been used in the experiment. Holes of 1 to 2mm in size have been drilled in the foam every two to three cells. Drilling holes in the foam seems to produce the best results to date. The drilled metal foam samples have a huge increase in their absorption coefficient and are able to absorb almost all the sound within the 1200 to 1600 Hz frequency range. Attempts have been made at drilling holes into previously rolled and compressed samples, but no benefits were seen.[4]

The effects seen with rolling, compression, and hole drilling can be fairly easily explained. Metal foam that has not been modified in such ways has closed cells for the most part and prevents sound waves from penetrating very far into the foam. By modifying the foam in any of the three described ways, the cells in the foam become cracked, allowing sound waves to proceed farther into the foam. Better results have been seen with the hole drilling, probably due to the fact that there is better control over the cracking of the cell structure. In any of the three cases though, better sound absorption capabilities are seen because the cellular structure of the modified foam allows sound waves to penetrate farther into the foam so that the waves can be absorbed. Metal foam may not be able to absorb sound quite as well as some other materials, but with some modification it may be used in place of those materials because of its strength.[4]

Thermal Conductivity of Metal Foam

A second potential application of metal foam is thermal insulation. Another appealing property of metal foam is its low thermal conductivity. Materials having a low thermal conductivity can be used as insulation. When the low thermal conductivity of metal foam is combined with its lightweight but strong structure, it is apparent that metal foam can be a great all-around building material. It can be used to support structures with its strength while insulating them at the same time.

The best way to classify how a material would work as thermal insulation is to calculate its thermal conductivity, [1]. Determining the thermal conductivity of metal foam is rather difficult due to its heterogeneous structure, consisting of both metal and the air, which is found in its pores. A number of different models can be used to calculate thermal conductivity constants, but one specific method produces the best results for determining the constant for metal foam. First, A. Minsar's model[5] can be applied in the following equation:

$$\lambda = \lambda_{sb}\left[1 + \frac{1 - \lambda_{sb}/\lambda_a}{1 - \prod^{1/3}(1 - \lambda_{sb}/\lambda_a)}\right] \qquad (6)$$

where λ_{sb} is the thermal conductivity of the solid part of the foam and λ_a is the thermal conductivity of the air found in the metal foam. π is the porosity of the foam and can be defined as follows:

$$\prod = \frac{W - m/\rho_{sb}}{W} \qquad (7)$$

where W is the volume, m is the mass, and λ_{sb} is the density of the solid portion of the foam. If it is assumed that there are no cracks in the material being examined, the pores are fairly spherical, and the air in the pores is just considered to be filler, then the thermal conductivity of the solid part is very large compared to the thermal conductivity of the air found in the foam. Therefore equation 6 above can be written as

$$\lambda_1 = \lambda_{sb}(1 - \prod^{2/3}) \qquad (8)$$

On the other hand, if it is assumed that there is a great deal of air in the sample and it basically surrounds the solid portions of the foam, the ratio of the thermal conductivity of the air to the solid part would be approximately zero. Then equation [6] could be written as follows:

$$\lambda_2 = \lambda_a[1 + \prod(1 - \prod^{1/3})] \qquad (9)$$

Due to the fact that there are many imperfections in metal foam, it can be assumed that the actual thermal conductivity of the metal foam would lie somewhere between the results that would be obtained using the above equations. Therefore, using a combination of the two equations results in the best approximation for determining the thermal conductivity of metal foam:

$$\lambda = a\lambda_1 + b\lambda_2 \qquad (10)$$

where $a + b = 1$ and each depends on the nature of the foam being examined. For example, if about 75% of the foam had few cracks and the air was just considered filler, a and b would equal 0.75 and 0.25 respectively.[5]

Even though the thermal conductivity of the metal foam can be calculated using the above formulas, the best way to determine its thermal conductivity is experimentally. Many different techniques can be used to measure the thermal conductivity of the foam, but none of them will be discussed in detail in this report. Rather this report will stress the results found from experiments. The experiments found that three different characteristics of the foam heavily influence the thermal conductivity. The first is the porosity of the metal foam sample; the more porous the sample, the lower the thermal conductivity coefficient. That is because the heat has to travel through an air medium, which does not have a high thermal conductivity compared to the metal itself. A more porous sample has much more air that the heat has to travel through, compared to a sample with a lesser amount of porosity. The second characteristic that can influence thermal conductivity is the shape and size of the pores in the foam. Larger and deeper pores cause the foam to have more air in it, which lowers the thermal conductivity. Lastly, the way the foam sample came into contact with the substrate being used causes the thermal conductivity values to vary. If the sample had a lot of metal securely bonded to the substrate, the value obtained would be much higher, but if many pores came into contact with the substrate, the thermal conductivity value obtained would be much lower.[5]

Thus, metal foam does not have a thermal conductivity as low as most other thermal insulators. The metal foam does have a thermal conductivity value about 30 times lower than the metal itself, but it still is not low enough to be considered a good insulator. The thermal conductivity of metal foam has been calculated both experimentally and through calculations using equations from the literature. The experimental results are quite comparable with the calculated values. With continued research, maybe the thermal conductivity of metal foam will become low enough to consider it for certain insulation applications.[5]

Conclusions/Final Thoughts

Researchers have created a very promising product. Metal foam has many interesting properties that make it versatile and appropriate for numerous applications. Most of its measured properties do not put metal foam at the top of any of the utility categories thus far, but with continued research and development, it could get there. As metal foam is further investigated, more uses will be devised for it, and someday we may see it in items we use every day.

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