Metal Foams Review and Possible Impact on the Naval Warfare during the Second World War

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Abstract

The purpose of this brief paper is to review historical and current metal foam technologies, and follow it with concise investigation of possible impact on the naval scene of the World War II, if they were used in manufacturing of ships. In order to do so, first, an overview of metal foam concept, properties and materials will be given in Introduction and Materials sections. Then processing methods are going to be introduced in two separate sections, first will focus on early ones, that were available during discussed time period, second will focus on the state-of-the-art methods available as this paper is written. Finally, examples of metal foams are going to be studied as materials for making a war naval vessel hull and compared with conventional materials.

Introduction

Metal Foams

Metal Foams is a category of composites (usually binary) composed of a metal and a filler material. The description of this category is very broad and, since it was proposed in 1925, number of types of materials enclosed in it has grown incredibly, with many commercially viable processes and products introduced to market through the last two decades, like for example race car crash absorber, shown in the Figure 1.

Figure 1. Race Car with "Crash Absorber" made of aluminum foam [3]

The main three properties of metal foams that can give them performance superior to a solid material are:

- Lower density, that can result in high strength and low weight, unachievable with any solid material. When combined with good structural engineering of the foam, it can result in higher specific strength significantly improved over the solid block. This allows not only improving the part performance, but also reducing amount of precursor material used if performance is to be kept constant.
- Energy absorption, that can be more than an order of magnitude grater compared to solid material.
- Morphology-controlled allowance of flow of gasses and liquids through the material. It can be used to create a material with extraordinary contact surface to volume ratio, for example for heat dissipation applications, or a material that restricts flow, even when it is fractured.

All of those advantages are going to be detailed further as function of technology used and morphology produced, and later investigated further in the Discussion section.

The main reason for this discussion being quite interesting is the fact that it allows to look at a great application for an emerging technology that can't be yet applied, because it is at too early stage, from a standpoint in the future, when it is well developed and characterized.

Overview on Demands for Vessel Hull Material Properties during the WW II

Power of the naval fleet during the Second World War was very closely related to the number of vessels (of certain types), as at that time technology used on ships, unlike nowadays, was quite uniform for all countries invested in the conflict, both in case of vessels guns and planes on the aircraft carriers.

The biggest factor that was limiting the number of ships that could be built was the raw material used for their production. A single battleship could be composed of more than 60 000 metric tons of steel, that needed to be first made from the ore.

During the war, despite big efforts from the US government to collect and use as much of spare steel from citizens as possible, few vessels that were supposed to be built had to be changed to smaller ones because of this shortage. One notable example being the Montana-class battleship.

Because of that limitation in supply of raw material, having a technology of producing a vessel of similar capabilities with only half of the material by weight, would have a game-changing effect. Therefore, having the mechanical properties per weight of the material as good as possible was in high demand.

Second demand was the shock absorbance and toughness of the material in general. This was due to the fact that most of ships sunk during naval battles were destroyed with torpedoes, with a few notable battles like Pearl Harbor, being due to the torpedoes only. In great simplification, a torpedo is a device that delivers an explosive closely to the ship and detonates it underwater next to it. This create a huge dynamic pressure wave that most often causes hull of the ship to crack and bend into the ship. This effectively sinks the vessel.

Because of that, an ability to withstand a torpedo attach would be of a great advantage during the WW II, as the ship would be protected most common vector of attack.

Materials

Two materials that are the most popular precursors of metal foams are aluminum alloys and structural steels. Both of those represent very good mechanical properties, and the choice between them is usually made based on specific demands for the application, with steel offering better strength per cost and aluminum alloys offering better strength per mass.

Processing Methods

Early Technology

The first concept of a metal foam was proposed over 10 years before the discussed time period, in the year of 1925 by a French scientist De Meller. [2] It was a general idea of lowering density of a metal part, by blowing air bobbles through molten metal in order to achieve pores of entrapped air. The original metal that was proposed for it was aluminum.

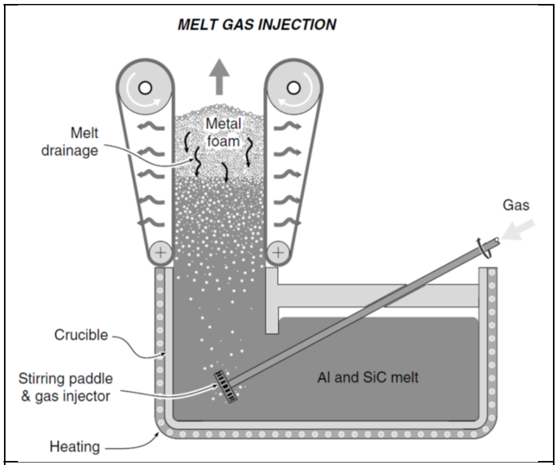


Figure 2. Metal Gas Injection Process [1]

In 1925, the idea for doing such a process was to pump air from the bottom of the crucible, in similar way to one shown in the Figure 2. One obvious disadvantage of it is that bobble distribution across the part is going to be highly non-uniform because system is highly asymmetric.

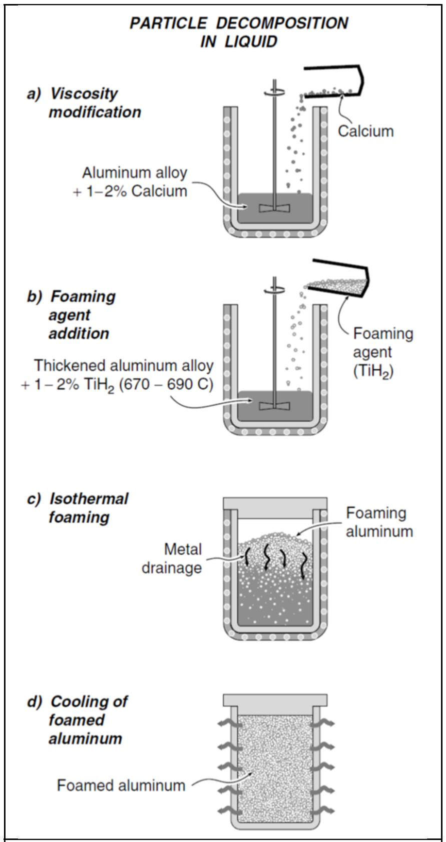


Figure 3. Particle Decomposition in Liquid Process [1]

Later in history, the same idea from 1925 was further developed and the blowing method, and its anisotropy, were the biggest changes to the process. Pumping gas was replaced with adding small (order of 50μm size) titanium hydride particles. At an elevated temperature of aluminum melt it decomposes into titanium and hydrogen, with hydrogen being in gaseous state. This release of hydrogen gas causes formation of bobbles with about 10mm diameter. A simple schematic of the process is shown in the Figure 3. The bobble size can be further controlled by stirring the material before the solidification occurs, making the size smaller and distribution more homogenous, as is presented in the example in Figure 4.

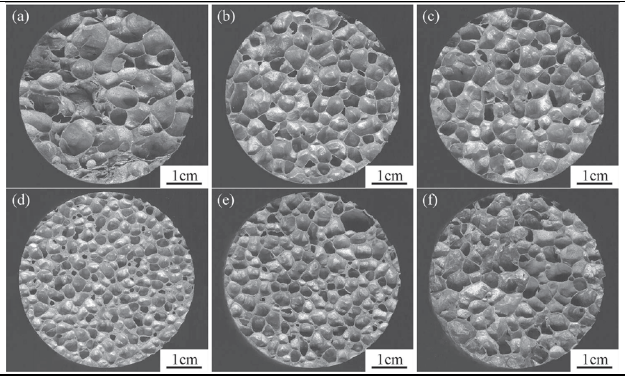


Figure 4. Cross-section of final metal foams formed at different stirring conditions. a) to d) show changes from 3 to 6 stirs/minute [2]

This change in cell size has also impact on the relative density of the material. At low value region, relative density is about directly proportional to it, as wall thickness is about constant and wall count is the most important factor. An example of density change with change in cell size is shown in the Figure 5.

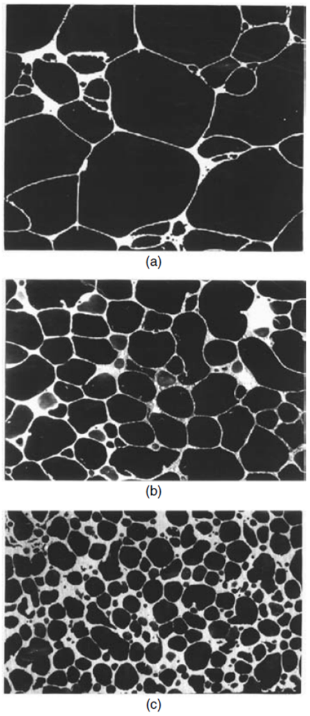
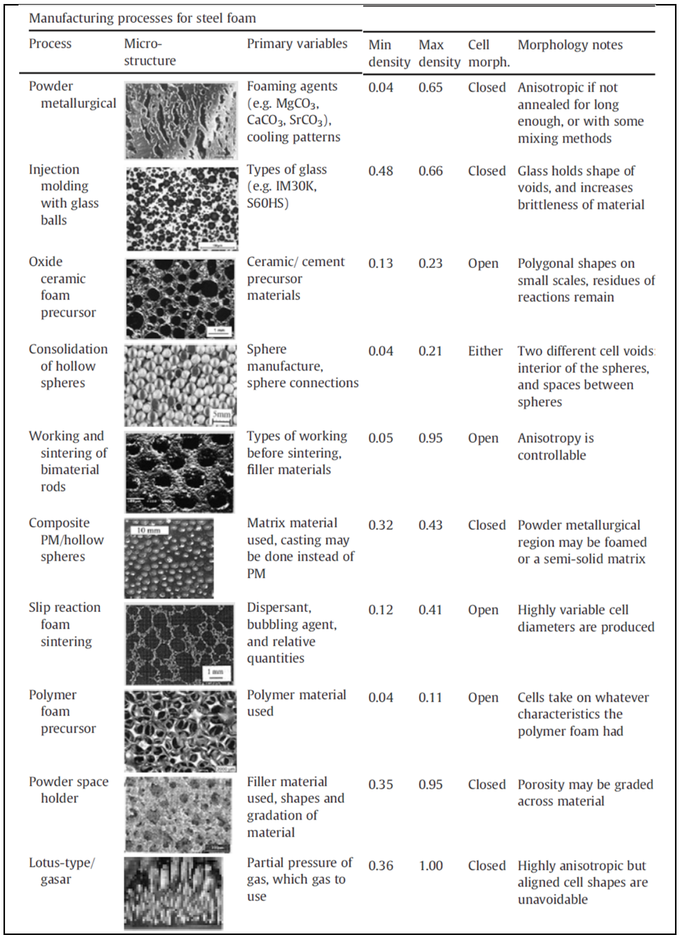


Figure 5. Illustration of increase in relative density with decrease in cell size. Bright field is the metal component. [1]

An important thing to point out is that the process of aluminum foam formation described above is the same as the one proposed in 1925, with only change being advancement in the blowing gas delivery method.

Current Processing Technologies Overview

Nowadays most of the research done is focusing on steel foams, as it is aimed at reducing the consumption of raw materials for civil engineering applications. A description of most important processing methods with resulting structure morphologies is given in the Figure 6 below.



Manufacturing processes for steel foam

Process	Micro-structure	Primary variables	Min density	Max density	Cell morph.	Morphology notes
Powder metallurgical		Foaming agents (e.g. $MgCO_3$, $CaCO_3$, $SrCO_3$), cooling patterns	0.04	0.65	Closed	Anisotropic if not annealed for long enough, or with some mixing methods
Injection molding with glass balls		Types of glass (e.g. IM30K, S60HS)	0.48	0.66	Closed	Glass holds shape of voids, and increases brittleness of material
Oxide ceramic foam precursor		Ceramic/ cement precursor materials	0.13	0.23	Open	Polygonal shapes on small scales, residues of reactions remain
Consolidation of hollow spheres		Sphere manufacture, sphere connections	0.04	0.21	Either	Two different cell voids interior of the spheres, and spaces between spheres
Working and sintering of bimaterial rods		Types of working before sintering, filler materials	0.05	0.95	Open	Anisotropy is controllable
Composite PM/hollow spheres		Matrix material used, casting may be done instead of PM	0.32	0.43	Closed	Powder metallurgical region may be foamed or a semi-solid matrix
Slip reaction foam sintering		Dispersant, bubbling agent, and relative quantities	0.12	0.41	Open	Highly variable cell diameters are produced
Polymer foam precursor		Polymer material used	0.04	0.11	Open	Cells take on whatever characteristics the polymer foam had
Powder space holder		Filler material used, shapes and gradation of material	0.35	0.95	Closed	Porosity may be graded across material
Lotus-type/ gasar		Partial pressure of gas, which gas to use	0.36	1.00	Closed	Highly anisotropic but aligned cell shapes are unavoidable

Figure 6. Manufacturing process for steel foam formation and resulting morphology [3]

One of the most important properties of a modern metal foam is its cell morphology, that can be either open or closed. As shown in the Figure 7 that gives some quantitative estimations of density and cell size, they are a crucial thing to consider if certain extremum of density or cell size is needed.

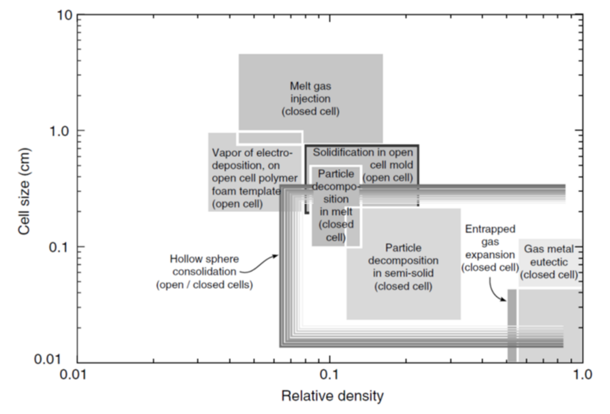


Figure 7. Cell Size vs Relative Density [1]

First and more intuitive to people, as they resemble soap foam in structure are closed cell foams. Those are morphologies where cells are not interconnected, but are independent or partially independent elements suspended in continuous matrix of regular metal. This allows to approximate them as discrete elements in a matrix and give a very flexible adjustment of relative density when it is in medium (about 1-1 ratio of filler to metal) to full (approximately no filler) region. The most important properties that are direct result of such morphologies are:

- No path through the porosity, resulting in the material being gas tight
- One defective cell has little effect on the whole material
- Higher specific toughness compared to the open cell

Two examples of processes that can be used to obtain such closed cell morphologies are particle decomposition, described before and shown schematically in the Figure 3, and hollow sphere processes, in which hollow spheres of metal are first formed to be later sintered or embedded in a continuous matrix of the same of different material. Figure 8 shows an example of such structure with spheres made of stainless steel and continuous matrix being aluminum alloy.

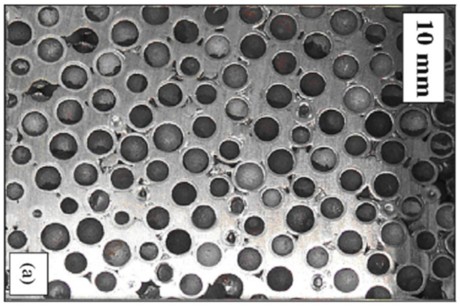


Figure 8. Metal Foam composite of steel hollow spheres in aluminum matrix [4]

Open cell morphology is one where single cells are interconnected with each other. This results in material that reassembles structure of a sponge or, at low relative densities, interconnected wires. An example of a method for creation of such structure is casting into polymer foam precursor (process #8 in the Figure 6 and 11), which schematic is presented in the Figure 9. The most important properties that are direct result of such morphologies are:

- Many pathways through the porosity, resulting in the material being able to pass gasses and liquids through, what can be very beneficial in applications where high surface area is desired, like in heat dissipation materials
- One defective cell can have strong effect on the whole material
- Higher specific strength compared to the closed cell thanks mostly to the lower density.

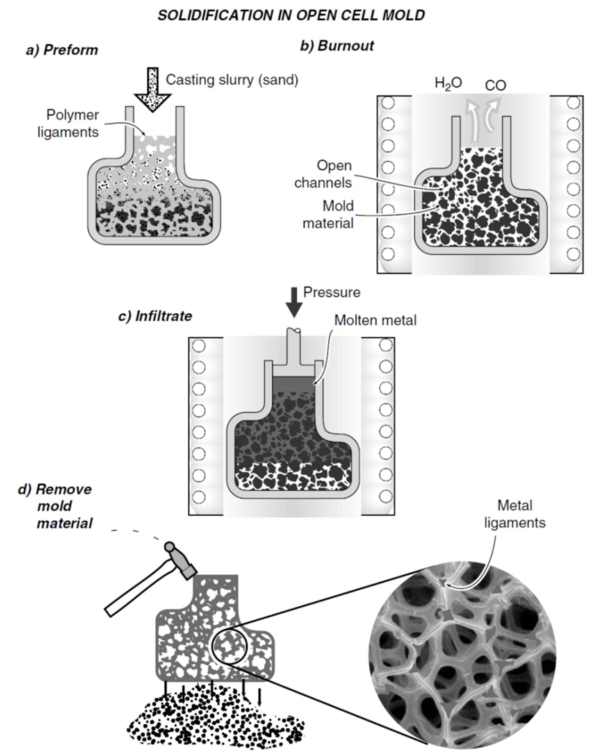


Figure 9. Open Cell Mold Casting [1]

The specific strength of such open-cell morphology can reach surprisingly high values if one of a few high-end manufacturing processes is employed. One of such processes is chemical vapor deposition (CVD) on a polymer substrate, which is illustrated in the Figure 10. One of its biggest advantages is that if it is combined with polymer additive manufacturing, like cheap and available fused deposition, it can create any structure desired by the engineer, as long as it has open cell morphology.

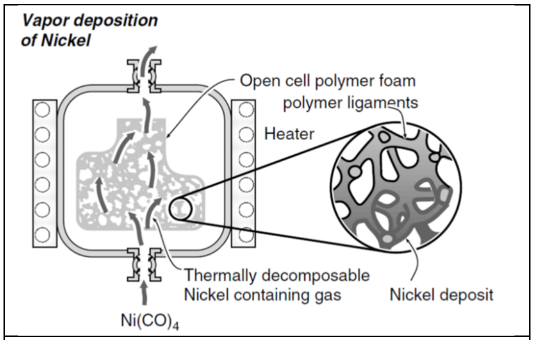
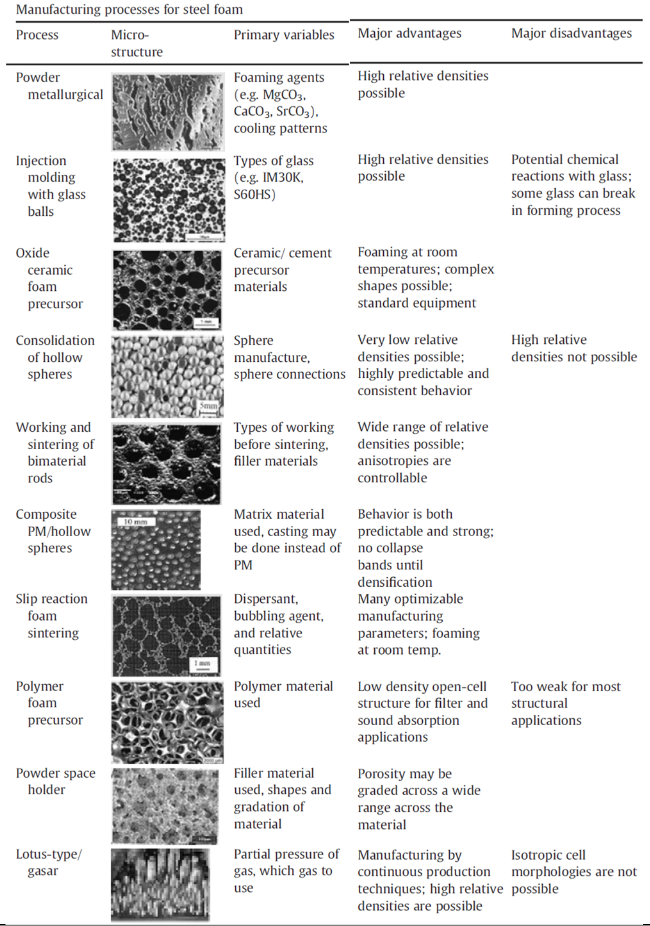


Figure 10. CVD of nickel on polymer matrix [1]

Figure 11 gives a summary of advantages and disadvantages of specific processing methods and can be compared with morphology description in the Figure 6.



Manufacturing processes for steel foam

Process	Micro-structure	Primary variables	Major advantages	Major disadvantages
Powder metallurgical		Foaming agents (e.g. $MgCO_3$, $CaCO_3$, $SrCO_3$), cooling patterns	High relative densities possible	
Injection molding with glass balls		Types of glass (e.g. IM30K, S60HS)	High relative densities possible	Potential chemical reactions with glass; some glass can break in forming process
Oxide ceramic foam precursor		Ceramic/ cement precursor materials	Foaming at room temperatures; complex shapes possible; standard equipment	
Consolidation of hollow spheres		Sphere manufacture, sphere connections	Very low relative densities possible; highly predictable and consistent behavior	High relative densities not possible
Working and sintering of bimaterial rods		Types of working before sintering, filler materials	Wide range of relative densities possible; anisotropies are controllable	
Composite PM/hollow spheres		Matrix material used, casting may be done instead of PM	Behavior is both predictable and strong; no collapse bands until densification	
Slip reaction foam sintering		Dispersant, bubbling agent, and relative quantities	Many optimizable manufacturing parameters; foaming at room temp.	
Polymer foam precursor		Polymer material used	Low density open-cell structure for filter and sound absorption applications	Too weak for most structural applications
Powder space holder		Filler material used, shapes and gradation of material	Porosity may be graded across a wide range across the material	
Lotus-type/ gasar		Partial pressure of gas, which gas to use	Manufacturing by continuous production techniques; high relative densities are possible	Isotropic cell morphologies are not possible

Figure 11. Manufacturing process for steel foam formation and resulting advantages and disadvantages [3]

Discussion of the Material for Application

Benefit of Availability

First and the most important thing to discuss, that was already partially covered in the Introduction it the benefit of using less material to construct a vessel with similar capabilities. During the peacetime manufacturing the raw material saving is not as important, since it is quite cheap and available in any quantity on demand. It effectively equates the benefit coming from materials savings with additional expanses in longer and significantly more energy demanding processing. However, during a large conflict like Second World War, when the whole country like US is switched to war-effort, the energy and manpower required during processing become less important, while at the same time material is in very high shortage.

If we consider for example the hull impact toughness as the primary criterion, a quite modest increase in specific toughness of foam by a factor two compared to solid part and ability to process it, would result in producing two warships instead of one.

Impact Toughness

The second biggest reason to consider metal foams for the hull is their impact toughness. First, one can look at what magnitudes of energies are to be considered. Figure 12 shows approximate peak pressure and impulse created on the material created by an explosion of certain mass of TNT at certain distance. Red line marked on the plot corresponds to 300kg of TNT detonated at 2m from the surface, what was a typical value for an average Japanese torpedo during World War II.

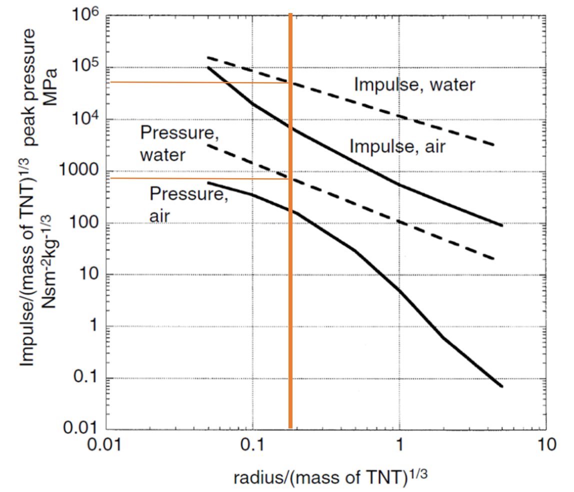


Figure 12. Peak pressure and impulse on the material surface vs mass and distance of the explosive. Red line corresponds to 300kg of TNT at 2m from the surface. [1]

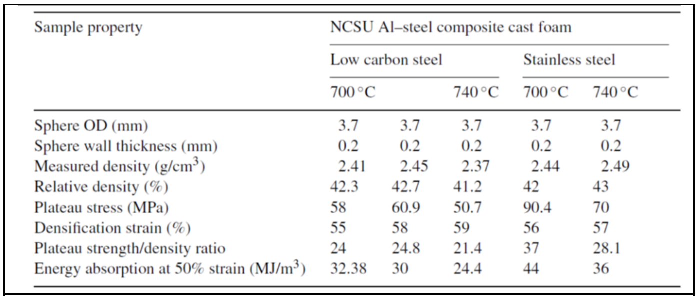
The mentioned numbers correspond therefore to 800 MPa peak pressure and impulse of 2.5*10^5 Ns/m^2. What can be used to calculate energy that the hull has to absorb:

$$U_i = \frac{1}{2}\rho_b b v^2 = \frac{J_i^2}{2\rho_b b}$$

with

$$h_{blast} = \frac{J_i^2}{2\rho_b b W_{vol}}$$

where J is the impulse, ρ and b are density and thickness of front plate that is pushed, and W being energy absorption per volume. Figure 13 shows mechanical properties of an example of low carbon and stainless steel hollow sphere – aluminum alloys, same as shown in the Figure 8 before.



Sample property	NCSU Al–steel composite cast foam				
	Low carbon steel			Stainless steel	
	700 °C		740 °C	700 °C	740 °C
Sphere OD (mm)	3.7	3.7	3.7	3.7	3.7
Sphere wall thickness (mm)	0.2	0.2	0.2	0.2	0.2
Measured density (g/cm^3)	2.41	2.45	2.37	2.44	2.49
Relative density (%)	42.3	42.7	41.2	42	43
Plateau stress (MPa)	58	60.9	50.7	90.4	70
Densification strain (%)	55	58	59	56	57
Plateau strength/density ratio	24	24.8	21.4	37	28.1
Energy absorption at 50% strain (MJ/m^3)	32.38	30	24.4	44	36

Figure 13. Properties of metal foam examples [4]

Let’s now consider a case where a hull of battleship is to be made the way that it can withstand a torpedo. Taking values obtained before and extracting energy absorption from Figure 13 for low carbon steel, with assumed front plate of 200mm which is a 50% of Iowa-class battleship hull thickness, we can calculate foam thickness required:

$$h = \frac{J^2}{2\rho b W} = \frac{(2.5 * 10^5)^2}{2 * 7700 * 0.2 * 30 * 10^6} [SI]$$

$$h = 670\ \text{mm}$$

Considering the density of the foam being 3.2 times lower than that of steel, this yields an equivalent of 210mm, what within some margin of error means that no additional material would have to be used compared to a solid hull, while at the same time it would provide the ship invincibility to torpedo attacks. This would require extreme change in the war tactics with great advantage on the technology adopter side and is a very good example of how using metal foams could change the war.

The one last quit point that should be made is that this technology is not used nowadays because such extreme change in naval war tactics was made when cruise missiles were introduced about a decade after the war and rendered vessel armor obsolete, while favoring active countermeasures taking down the missile before impact.

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