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Investigation of damping in porous metal foams

Bilal FETTAH [*], Hamou ZAHLOUL

Laboratory of Rheology and Mechanics, Hassiba Benbouali University of Chlef, Algeria

**Corresponding author, e-mail address: ba.fettah@univ-chlef.dz*

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ABSTRACT

Damping in materials and structure is known by the dissipation of energy over time under eventual action of an excitation called force. It is crucial characteristics in various engineering applications including civil engineering, mechanical engineering and aerospace engineering. It contributes to the safety, performances and longevity of these structures as well as the designed damping systems can improve the comfort and reliability of a wide range of engineering applications from everyday vehicles and machine to large scale engineering projects. The aim of this paper is to investigate damping mechanism in porous metal foams, the influence of different parameter such as porosity and microstructure on the damping phenomena and some practical implications. This research unlocks full potential of metal foams for vibration control and energy dissipation, advancing engineering solutions for a wide range of industries.

1. INTRODUCTION

In the past several decades, porous metal foams have played an important role in the development of various sectors. There are fast growing of its applications in medicine, mechanic, civil, marine and aerospace engineering. Foamed metals are porous materials which contains pores generally are open or closed. A common strategy used to manufacture metal foams is by preparing the blowing agent as a gas source to a molten metal then engineers add stabilized particles to the melt in order to obtain a uniform metal foam structure. Porous metal foams are lightweight material and typically retain some physical properties of their base metal. one of the major topics to be investigated in porous metal foams field is damping, it is crucial property in various applications.

Porous metal foams have excellent mechanical damping compared to the parent metal of which they are made [1]. Considering the internal damping is a form of dissipated energy within a material if it subjected to a cyclic stress, very limited knowledge is available about understanding mechanical damping and mechanisms of internal friction in porous metal foams [2]. At macroscopic approach, it is conventional that the dissipation of energy is the plasticity of a part of the system, high external forces generate important internal stresses that directly affect the mechanisms of generated damping. At microscopic level, we can distinguish damping in porous metal foams one by thermomechanical effects which considers damping in metals can be describe by the presence of thermal diffusion phenomena [3], the other by energy effects [4].

Although positive finding was presented in some research activities, predicting damping properties for porous metal foams in such application using finite element software is still missing.

However, damping determination of porous metal foams has rarely been analyzed. The only study on the damping properties of porous metal foams is that of [5] which they established first measurement related to damping loss factor in highly porous aluminum foam (up to 81.3%), they found that higher porosity produced higher loss factor damping. Banhart 1996 [6] enhances the finding of [5], they proposed a method to measure the loss factor of AlSi2 aluminum-silicon alloy foams of various densities with two types of special mount specimen. Beams as rectangular cross sections were normally used and driven into flexural vibrations, they concluded that damping is strongest in specimen with lowest apparent densities.

With the rapid growing of using porous metal foams in various applications, studying the damping and its structure dependence is a major concern. The way of producing open celled porous metal foams and the number of pores also effects on the damping and relative dynamic modulus behaviour [7].

Massimo Goletti et al [8] determined the damping parameters of aluminum foams beam by using two different test configurations based on vibrational method which they are modal shaker and instrumental hammer. They used the ASTM standard 2010 [9] to compute the loss factor for specific 3 eigenmode. They mainly found that the damping ratio is constant over frequency with the two different setups.

Furthermore, many studies have been carried out to investigate the effect of porous metal foams to eliminate the undesired vibrations of mechanical structures. Albertelli et al [10] proposed numerical simulation based on the finite element method to estimate damping in aluminum foamed filled tube in order to support the simple mechanical structures such as machine tools and its components.

Damping coefficient depends on the number of pores of porous metal foams. L.Dahil et al [11] investigated the effect of aluminum foams porosity on damping ratios by using experimental modal analysis method. It was observed from the frequency charts that the damping ratios increases with increasing the porosity.

In practical application, the demand for high strength with high damping of porous metal foams are necessarily required for ensuring good functionality and high safety. Many methods have been developed to improve damping properties in complicated structure for example in porous metal foams filled steel tube [12], it was found that under large vibration amplitude, the open pore aluminum foam and closed pore aluminum alloy can increase the level of mechanical damping more than five times than the steel tube itself.

Wang et al [13] improved the strength and enhance the damping properties of the nickel foam produced by chemical vapor deposition technique. They investigated the addition of graphene layer to the nickel foam ligaments in order to obtain both high strength and damping properties.

For this study, it was of interest to investigate damping in porous metal foams because it is an important area of research with implication for various engineering applications. Also, to develop a comprehensive understanding of the damping behaviour in porous metal foams by investigating the damping mechanisms at multiple scales. This research presents some practical advantages for readers to understand the phenomenon of damping in porous metal foams.

2. DAMPING MECHANISMS IN POROUS METAL FOAMS

Porous metal foams become well known material among researchers, they offer multiple potential for lightweight structures, energy absorption and for thermal management. Generally damping in materials and structure is very important to restrict mechanical vibrations and establish security and comfort. Previous studies have emphasized that Nickel Inconel superalloy and copper foams have shown promise for noise control and vibration suppression due to their unique mechanical properties [1]. These foams have high stiffness, excellent energy absorption, and good vibroacoustic damping. Despite their potential, porous metal foams are not widely used, but research and advancements in manufacturing processes are expected to increase their accessibility in the future [14]. Current methods, such as experimental modal analysis and finite element simulations, only provide valid results for specific structures and cannot predict damping behavior in new systems. To address this limitation, predictive models for damping properties have been developed. These models involve experimental tests and simulations on simple structures to define critical damping values. Based on these results, predictive models of damping factors can be established and validated on different structures.

Damping refers to the ability of a material to dissipate energy from mechanical vibrations. In the case of porous metal foams, their low density compared to traditional metals allows for promising damping capabilities relative to weight. Various mechanisms contribute to the damping behavior of cellular metallic materials. Many internal friction mechanisms that are present in dense metals also contribute to the damping in porous metal foams. The density of these foams can be as low as 1/10th or even lower than that of the metals used for their carcass [1]. This low density contributes to their potential for efficient energy dissipation.

There are several ways to characterize material damping. The loss coefficient η will be used to define the terms of energy dissipation. If a material is loaded elastically to a stress $\boldsymbol{\sigma_{max}}$ (see fig 1) it stores elastic strain energy per unit volume, U; in a complete loading cycle it dissipates ΔU, shaded in the fig 1, where:

$$U = \int_0^{\sigma_{max}} \sigma d\varepsilon = \frac{1}{2}\frac{\sigma_{max}^2}{E} \ \ and \ \ \Delta U = \oint \sigma d\varepsilon$$

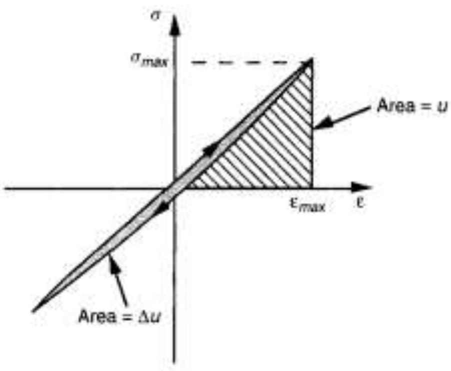

Figure 1. loss coefficient η measures the fractional energy dissipated in a stress-strain cycle [1]

The loss coefficient η is the energy loss per radian divided by the maximum elastic strain energy (or the total vibrational energy)

$$\eta = \frac{\Delta U}{2\pi U}$$

In general, the value of η depends on:

- frequency of cycling.
- temperature.
- amplitude of the applied stress or strain.

Other measures of damping include:

The proportional energy loss per cycle.
The damping ratio ξ.[15]
The logarithmic decrement δ.[16]
The loss angle ψ.
The quality factor Q.

Damping mechanisms in metal foams can be enhanced. With direct growth of graphene on the metal surfaces opens a door for high performance composites in a simple manner. Wang et al [13] investigated damping characteristics and mechanical strength of nickel foams by placed a graphene layer on the top surface of the porous foams specifically on the cell walls.

3. EFFECT OF POROSITY ON DAMPING

Porous metal foams have been found to possess high damping capabilities, with internal friction increasing as porosity increases and pore size decreases. This damping behaviour is independent of frequency and primarily depends on strain amplitudes. Metal foams with porosity values over 50% are particularly effective at attenuating vibrations, making them of interest to designers. In addition to their damping properties, metal foams also offer advantages such as a low weight-to-

Figure 2. Aluminum foam of 86% porosity.

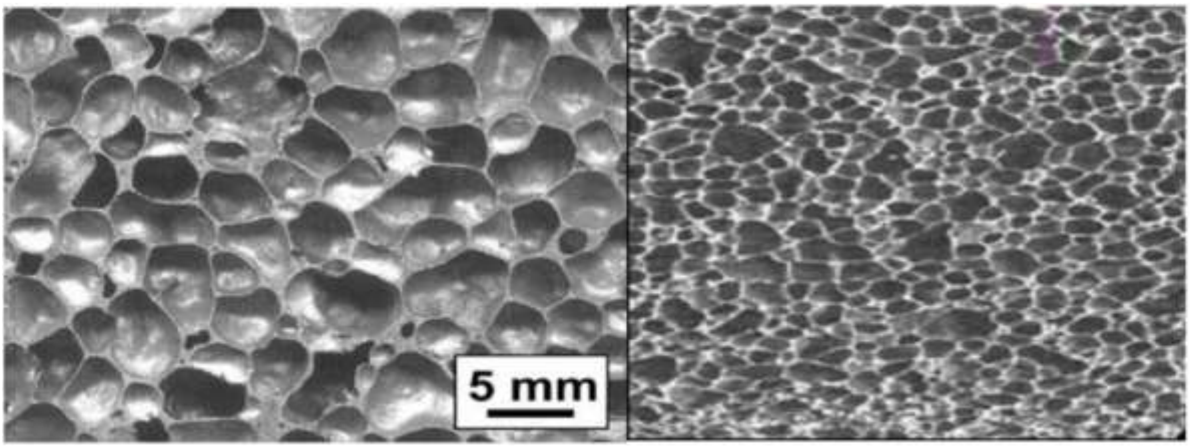

Figure 3. Closed cell aluminum foams [18]

stiffness ratio and high energy dissipation capacity, making them attractive for various industries [17].

3.1. Type of Porous Metal Foams

Metal foams can be divided into two types according to [18].

3.1.1. Closed Cell Metal Foams

The closed cell metal foams group (see fig 3) are appropriate for structural applications, such as energy absorbers or load bearing components, where light solutions are often built on stiffness/weight ratios that are as high as possible.

3.1.2. Open Cell Metal Foams

The open metal foams group (see fig 4) are mostly used in functional applications such as heat exchangers, filters, silencers, and catalyst support, where a liquid or gas must pass through the foam's degree of porosity.

Metal foams have been proposed for damping and anti-crash applications due to their energy-absorption properties. The damping properties of foam-filled tubes improve with the number of cycles, making them suitable for applications where damping is crucial. Open-cell nickel foams, in particular, are widely used in battery electrodes and exhibit unique features such as permeability, high tortuosity, and excellent electrical and thermal conductivity. Despite their desirable properties, the fabrication of metal foams still faces challenges due to the coexistence of solid, liquid, and gaseous phases at different temperatures. However,

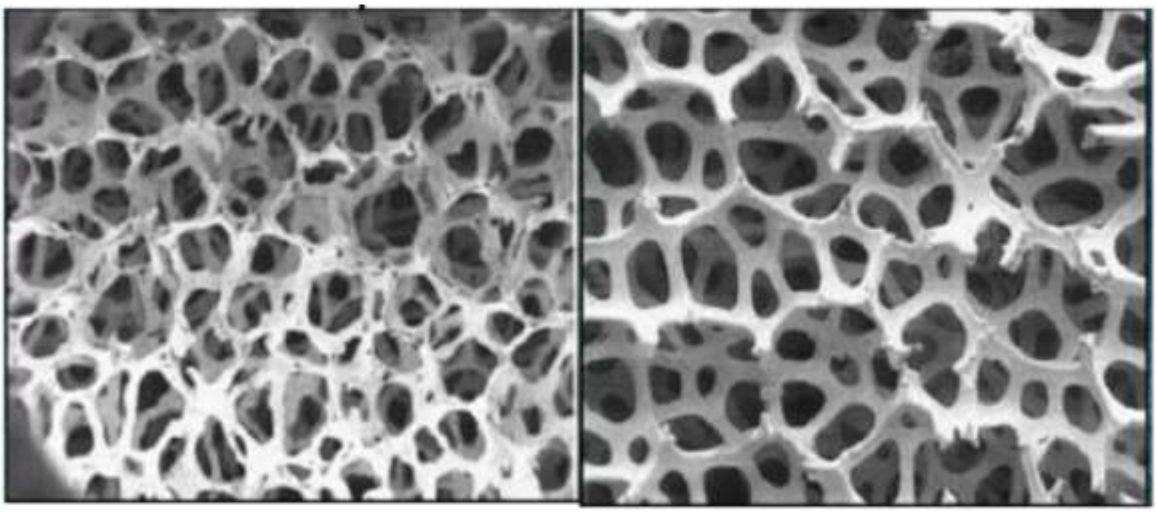

Figure 4. Open cell aluminum foams [18].

extensive research has provided valuable insights into the damping mechanisms and properties of porous metal foams. The damping behaviour of porous metal foams materials is influenced by various mechanisms of internal losses, such as thermoelastic and microeddy currents, magnetic domains, dislocations, and microcracks.

Porosity and specific foam structures are important factors that affect the damping characteristics of porous metal foams. Higher porosities often lead to better damping performance due to increased internal friction and energy dissipation.

4. FUTURE APPLICATION OF POROUS METAL FOAMS

The main applications of porous metal foams can be grouped into structural and functional and are based on several excellent properties of the material [18]. Structural applications take advantage of the lightweight and specific mechanical properties of metal foams; functional applications are based on a special functionality, i.e., a large open area in combination with very good thermal or electrical conductivity for heat dissipation or as electrode for batteries, respectively. We will review the applications of closed, partially open and open cell metal foams.in this section of the paper we will cite multiple application where foams are actively utilized.

4.1. Structural Application of metal foams

- Automotive industry [19]
- Energy absorption [20]
- Lightweight construction [2]
- Noise/sound absorption [19]
- Aerospace industry [21]
- Ship building [14]
- Railway industry [14]
- Machine construction [22]
- Biomedical industry

4.2. Functional Application of metal foams

- Filtration and separation
- Heat dissipation and cooling elements
- Support for catalysts
- Thermal storage energy application [23]
- Silencers [1]
- Fluid flow control
- Battery Electrodes [2]
- Spargers [1]
- Water decontamination and Acoustic control.

The open literature shows that porous metal foams are one of the most promising materials for fulfilling the increasing demands where certain properties such as acoustic, damping and thermal characteristics are required. However, metal foams have limited noise absorption capability but still enough to be useful for various multifunctional applications in different sectors.

To note that these properties make porous metal foams more attractive in engineering applications such as electro-shielding, blast mitigations, aerospace industry, and in many more applications that are not mentioned here but open to the imagination of engineers and researchers.
The future of porous metal foams is bright. It is well evident that the use of state-of-the art metal foams is fast growing. Their utility in several fields of industry such as aerospace, automotive, construction, etc., is driving their demand for mass production.

Technological advancements in recent years have also led to increased production capacity. In comparison to conventional materials, metal foams can be produced at a lesser cost. Development of models will further help in increasing the production rate, properties, quality, and durability. The last but equally crucial aspect is the cost reduction of foam structures which will ensure aggressive quantitative and qualitative growth of the market in future.

Currently, very limited types of materials are explored in their foam counterpart. Aluminum, nickel, cobalt, and steels are the most investigated ones so far. There is an urgent need to exploit more and environment-friendly and stable metals for use as foams. The potential areas of applications are progressively and rapidly emerging due to massive research in this field in finding the appropriate combination of metals or alloys for satisfying the on-field demands of size, shape, density, strength, stiffness, energy absorption, acoustic behaviour, etc. Further, as fuel and energy conservation are extremely sought after to avoid global warming, it is likely more applications will emerge in that direction and hence exploring new materials is very critical at this juncture.

4. CONCLUSION

In conclusion, the research on damping in porous metal foams and its applications has shown great potential. The influence of porosity on damping properties was examined, revealing the intricate relationship between pore size, distribution, and damping behaviour. We uncovered the frequency-dependent nature of damping, a crucial aspect in vibration control applications. The development of metal foams as engineering materials for functional and structural applications is still ongoing. Continued efforts in characterization, modelling, and production techniques will further enhance the understanding and utilization of metal foams in various industries. The versatility of metal foams makes them attractive for a wide range of applications, from structural elements to heat exchangers, energy absorbers, and sound damping elements. With further advancements, metal foams are poised to make significant contributions in the field of materials science and engineering.

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