Damping of Structure-borne Sound with Particle – filled Metal Hollow Spheres

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Abstract

According to the directions of European Union for nearly all machines noise control arrangements are needed (EU environmental noise directive 2002/49/EC). Additional e.g. automotive industry requires light-weight materials to reduce the total weight of their cars which led to significant reduction of the CO_2 emission. The combination of both requirements can't be fulfilled by any to date existing material. Cellular materials in particular are suitable for applications in light-weight constructions, but even those materials until now exhibit too low damping of structure-born sound. The damping behaviour of particles witch are filled in cavities are well known. Hence, a technology was developed to synthesize particle filled metal hollow spheres (pfMHS). Light-weight materials made with these particle-filled metal hollow spheres reach e.g. damping of structure-born sound and Young's modulus like lead by less then one-fifth of its density. Thanks to the multitude of parameters density, Young's modulus and damping are tuneable in a wide range.

1. Motivation

Cellular materials are developed to fulfil the demands of Energy- and CO_2- reduction in applications by weight reduction and to reduce the material requirements in production. But cellular materials present additional properties like energy absorption, thermal insulation and damping of air-borne sound. The mean mechanisms of damping of air-borne sound are the reflection of acoustic waves and the elongation of their routes. Conventional cellular materials show only low damping of structure-borne sound. Unfortunately damping is decreasing with increasing Young's Modulus of the materials. The reason is that vibration energy and so the dissipated energy is proportional to the Young's Modulus. That means an additional damping mechanism is needed. Today structure-born sound is damped by heavy materials or polymers. All metals damp by the thermoelastic effect. It means the temperature of an elastic dilated grain decreases slightly. By warming back it dilates further and gives additional stress to the neighbouring grains.

This effect is relative small. Metals can also damp by other reversible processes like movement of dislocations, twinning, or strain-induced martensite transformation. The friction of inner surfaces such as cracks is the mean damping mechanism in porous ceramics and a similar origin has the damping of cast iron. Rubber and other polymers damp by reversible sliding of carbon-chains. Cast iron or lead are too heavy for light-weight constructions and polymers like rubber and wood are not inert against to some environmental conditions and lose their damping properties by low and high temperatures. In some cases impact damper are used for damping of structure born sound. These are present cavities which are fulfilled with sand or other granular materials. The mean damping mechanism of impact dampers is the dissipation of mechanical energy by partially elastic impacts of the enclosed particles with each other or with the wall of the container. Particle-filled metal hollow spheres are invented to use this damping mechanism for cellular materials. So each particle-filled metal hollow sphere is a minimized impact damper with all advantages of metal hollow spheres and the additional ability of vibration damping.

2. Manufacture

A double Spray-coating process is used for manufacture of pfMHS. Spheres made of expanded Polystyrol are coated in a fluid bed process first with a ceramic powder layer and in a second step with a metal powder layer. After sintering the metal shell has only a low and closed porosity and no ceramic inlays, which would act as defects. The ceramic particles inside the spheres are free movable. This is the pre-condition for damping.The sintered pfMHS can be glued, cast in polymers or metals, or brazed to build up components.

3. Damping ability of single spheres

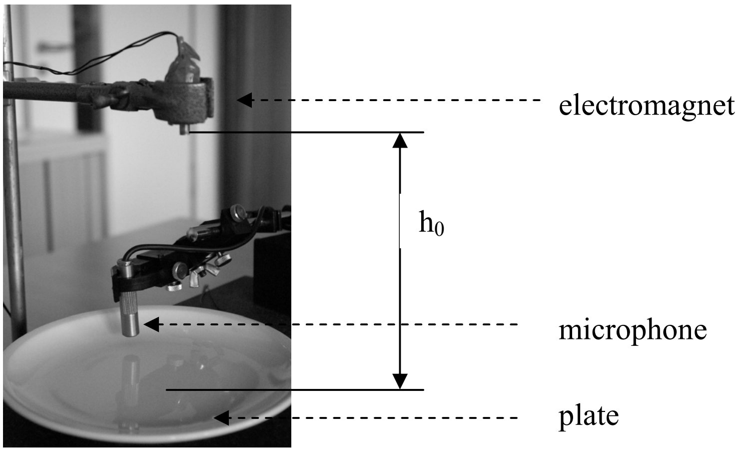

FIGURE 1. Measurement set-up for testing of single spheres

For testing of the damping ability of single spheres the measurement set-up shown in FIGURE 1 was created. The pfMHS is hold in a definite high (h_0) and has the potential energy E_{pot}. It falls down and hit the plate. The potential energy is transformed in kinetic energy (E_{Kin}). During the impact on the plate the kinetic energy is partially dissipated. The coefficient of restitution ε describes how much energy remains in the sphere:

$$\varepsilon = \frac{E_{Kin,after\_Impact}}{E_{Kin,before\_Impact}} \qquad (1)$$

After hitting the plate the sphere springs upwards, where the velocity is given by the remaining kinetic energy. Because of the gravity the sphere falls down again and hits the plate a second time. With every impact the plate starts to vibrate and emits a sound. This is recorded by a microphone with a high resolution. The time lag between the first and the second impact is known from the recorded signal. It is easy to compute the coefficient of restitution by the theorem of conservation of mechanical energy and the equation of motion for the vertical throw upwards. In equitation (2) g is the gravitational acceleration, Δt is the time lag, and h_0 is the starting high. For the coefficient of restitution follows:

$$\varepsilon = \frac{g}{8 \cdot h_0} \cdot \Delta t^2 \cdot 100\% \qquad (2)$$

100%-ε describes the dissipated energy during the first impact.

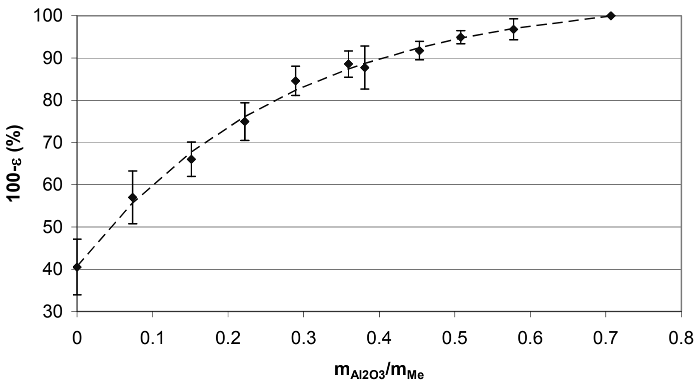

FIGURE 2. Influence of mass relation on the dissipated energy

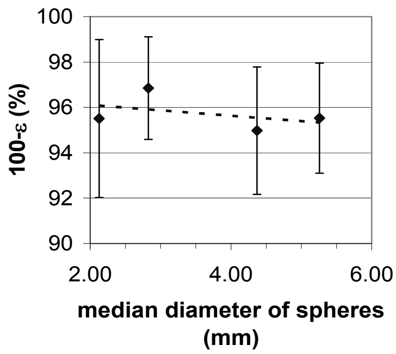

FIGURE 3. Influence of sphere diameter on the dissipated energy (mAl2O3/mMe=0.55; Average metal density: 0.7…0.8)

FIGURE 2 shows the increase of the dissipated energy by increasing mass relation of particle mass inside the hollow spheres (m_{Al2O3}) to the mass of the metal shells (m_{Me}). The average metal density – it means the thickness of the shells – of the hollow spheres has no influence by a constant mass relation. The influence of the diameter of the spheres is only very small (FIGURE 3).

4. Computer Simulation of particle movement during single ball testing

It was started with a computer simulation of the particle movement in the metal hollow spheres during single ball testing. It describes the movement of particles (small circles) and hollow sphere (big circle) from the first to the second impact. The program builds up by adding physical mechanisms step by step. TABLE 1 gives the abstractions made for the first simulation program. FIGURE 4 shows the start positions of the components at the moment of the first impact.

TABLE 1 Abstractions made for the first Simulation Program

Reality	1. Simulation Program
3D Hollow sphere	2D Circle
coarse and porous inner surface	plane circle
Particles with different weight and geometry	equal sized circles with equal weights
peripheral impacts leads to rotation of particles and shell	only central impacts with no rotation
partially elastic impacts between particles	completely elastic impacts
vibration of shell	no vibration
unknown start position of particles	average between chosen start positions
$\sim 10^5 \ldots 10^7$ particles per sphere	20…100 circles

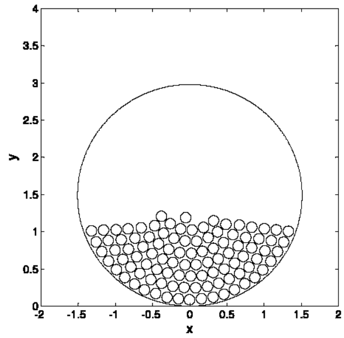

FIGURE 4 Start Positions for Computer Simulation

After including the first vibration mode of the shell, different sizes of the inner circles, and increasing their number up to 100 the first results are qualitatively similar to the experiments. It was shown at model spheres that for more congruence it is necessary to add the third dimension and not central impacts. This leads to rotation of particles and shell, which stores a not negligible part of the energy.

5. Damping of samples

The damping of samples was measured by Impulse Excitation technique (IET). FIGURE 5 shows the bedding of the samples in the nodes of the first vibration mode for bending. The emitted sound after a weak impact at the anti-node is recorded and analysed. The damping η is calculated by equation (3):

$$\eta = \frac{k}{\pi \cdot f} = \frac{\Delta E}{2\pi \cdot E} \qquad (3)$$

k is the exponent of the “e-function” which defines the velocity of dying out, f is the frequency of the vibration, E the energy of vibration and ΔE the dissipated energy of one cycle.

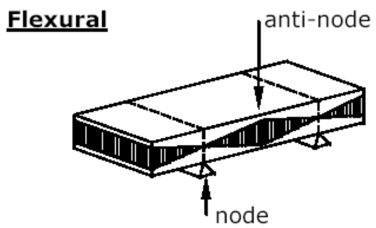

FIGURE 5. Bedding of the sample for IET

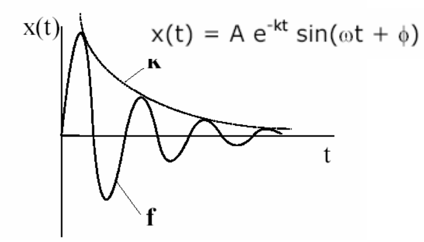

FIGURE 6. Amplitude of damped vibration [5]

FIGURE 7 shows the increasing damping by increasing mass relation of used pfMHS. The damping of the samples where the pfMHS cast in epoxy is generally lower than the damping of the glued pfMHS. The reason is the storage of vibration energy in the epoxy matrix. To demonstrate that the damping is caused by the particle filling, different amounts of unfilled and particle filled metal hollow spheres were cast in epoxy (FIGURE 9). All parameters of filled and unfilled spheres are the same, except the particle filling. The results are shown in FIGURE 8.

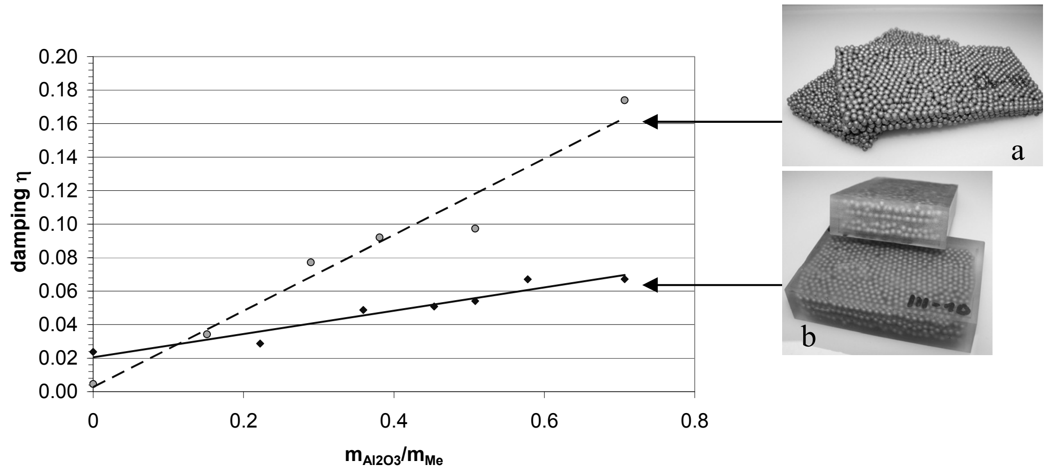

FIGURE 7. Influence of mass relation of spheres on the damping of glued samples (a) and cast in epoxy samples (b)

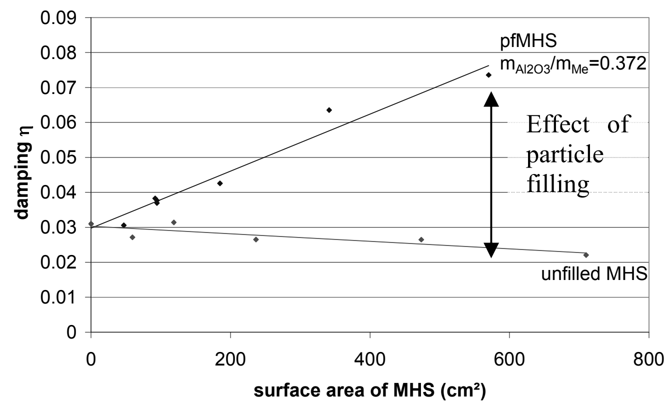

FIGURE 8. Influence of particle filling on damping of samples

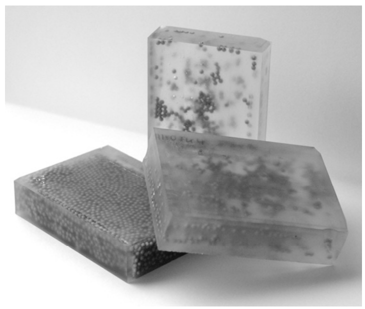

FIGURE 9. Samples cast in epoxy with different amount of MHS

The damping of the samples with unfilled metal hollow spheres is decreasing because epoxy has a higher damping ability than unfilled metal hollow spheres. The difference between the 2 curves in FIGURE 8 exhibits the pure effect of the free movable particles inside the pfMHS.

6. Comparison to reference materials

FIGURE 10 and 11 show the damping, Young's Modulus, and density of the samples made with pfMHS in comparison to reference materials. All measurements made with IET on one measurement set-up.While bulk metals, even such as used for damping machine tools like cast iron, have a damping ability lower than 0.001, all composites with pfMHS are be found two orders of magnitude higher. The Bulk metal with the highest damping is lead; it is be found with the same damping like our first sample pfMHS cast in Al-alloy. The Young's modulus is nearly similar. As the high density of lead nobody would use it for damping a light weight construction, with pfMHS this damping ability becomes available for light weight design. While polymer materials and lead not operational for high temperatures and in harsh environmental atmospheres, the damping mechanism of particle filling still works.

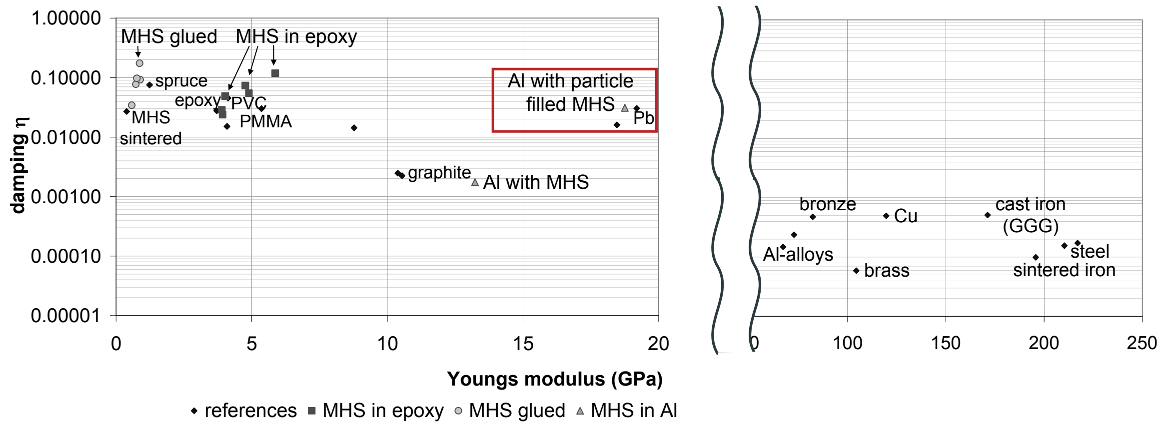

FIGURE 10. Damping against Young's Modulus - Reference materials and pfMHS glued, cast in epoxy, and in Al-alloy

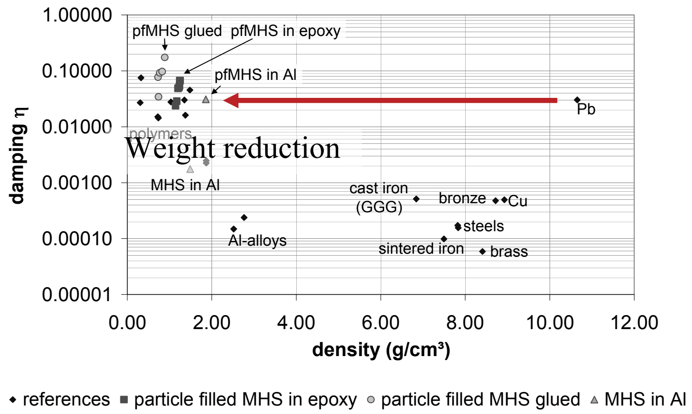

FIGURE 11. Damping against density - Reference materials and pfMHS glued, cast in epoxy, and in Al-alloy

7. Conclusion

Particle filled metal hollow spheres cast in Al-alloy reach a similar damping and Young's Modulus like lead by less then 1/5 of its density.

Future work will be done to improve the damping and Young's modulus by density less than 5 g/cm³ and to reduce process steps to decrease the production costs.

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