Correlation of mechanical properties with the acoustic properties in case of an experimental white cast iron

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Abstract. The general and traditional opinion regarding the materials used to build bells, musical instruments or sound transmitters is that those materials must be only from the bronze alloyed with tin category. In order to approach this idea from a scientific point of view, the materials with acoustic properties must be analyzed starting from the physical theory and experimental determination that sound travels only through bodies with elastic properties. It has been developed an experimental white cast iron, medium alloyed with Cr and Ni, in order to obtain a material with special acoustic properties. There were determined on specific samples: the vibration damping capacity, the unit energy, the tensile strength and elasticity modulus. These properties were correlated with the properties of other known acoustic materials.

1. Introduction
Alloys used for musical instruments, sound devices or transmission of sounds manufacture production (bells, sound transducers etc.), must fulfill some specific technical requirements.

Choosing materials for this purpose and their testing is essential in order to find solutions optimized both in terms of production and in transmission sound properties, but also regarding the service life.

In accordance with the principles of solid body physics, sounds propagate only in solid bodies with elastic properties, in consequence, the elastic properties are fundamental in the analysis of materials for the construction of such as devices.

The elastic properties of a material is evidenced by some indicators that can be measured by physical methods, thus regarding the link between tension and deformation elastic modulus is defined and in terms of mechanical strength is defined the elastic limit, the tensile stress at yield [1, 2].

In most cases the design and implementation of technical objects these two indicators, (E, σc) are enough, but not the not for design and implementation of instruments of production and transmission of sounds, where there is an additional size, called damping capacity or internal friction. This characteristic produces a phase shift between the stress and the strain and is a negative factor in the production and transmission of sound. Current standards for products may highlight only the elastic modulus and yield strength, which makes impossible the choice of material for the design of a device for the production and transmission of sounds.
Determination of the damping capacity for one material can be achieved by several methods and the experimental results are shown by means of some well-defined measurements. (Damping logarithmic decrement, \( D \), tangent of the phase shift angle, \( \tan \delta \), quality factor \( Q^{-1} \)). The damping degree and the elastic limit depend on several factors, but mostly by the material nature.

2. Methods and materials

It has been developed an experimental white cast iron, medium alloyed with Cr and Ni, in order to obtain a material with special acoustic properties. There were determined on specific samples: the vibration damping capacity, the tensile strength and elasticity modulus. These properties were correlated with the properties of a known acoustic material, a CuSn and AlSi alloy. These last two alloys are chosen for their known acoustic properties: CuSn is a usual bell alloy, and AlSi is a duralumin alloy type.

For material research regarding the sound, for testing damping capacity, was designed a simple, but quite accurate method, which consists of pouring a tuning fork from the studied material, followed by a computer analysis of sound oscillograms produced by tapping.

For this purpose has been developed a tuning fork with a geometric configuration which allows to achieve a maximum amplitude of the fundamental frequency, figure 1. After casting the tuning fork is tested by a computer program using a microphone attached to the tuning fork in the laboratory.

After casting and removing the casting network, the tuning fork is meticulously cleaned and checked for any casting defects. In figure 2 are presented the three tuning forks after being prepared for the sound test.

In figure 1 is presented the tuning fork with its calculated dimensions and also with the specific components and working areas.

Fastening the rubber handle with a screw for mounting microphone on the tuning fork body, then the microphone will be connected to the corresponding socket of the computer, then will check by tapping if the system works.

**Figure 1.** Tuning fork with dimension; 1. tuning fork arms; 2. tuning fork body; 3. grip rubber material mounting hole; 4. microphone location.

After starting the program for the sound analysis, will hit the tuning fork and record the oscillogram, operation is repeated several times to get a better accuracy. Oscillogram is subjected to analysis to determine the requested investigated measurements (amplitude, degree of damping).

In order to have a milestone in terms of the effect of heat treatments applied to special casted alloys we did a study on the producing sounds properties for casted samples without incurring heat treatment.

Most of casted objects for the production and transmission of sounds, such as bells, piano plates etc, are not subjected to heat treatment after casting, not knowing the effects of heat treatments on their functional role.
For this purpose the three alloys were investigated. Chemical composition was determined using the spectrometer Foundry Master that is present at the Materials Science Faculty of Iasi. The results are shown in the tables 1, 2 and 3.

Table 1. Chemical composition of the white cast iron.

| Element | Fe | C  | Si   | Mn  | P  | Cr | Ni | Mo | Cu |
|---------|----|----|------|-----|----|----|----|----|----|
| [wt %]  |    |    |      |     |    |    |    |    |    |
| Bal.    | 2.57| 2.67| 0.773| 0.09| 4.28| 5.43| 0.23| 1.15|

Table 2. Chemical composition of the casted aluminum alloy tuning fork.

| Elements | Al | Si | Fe  | Cu  | Ni | Mg | Cr | Zn | Other |
|----------|----|----|-----|-----|----|----|----|----|-------|
| [%]      |    | 0.11| 6   | 2.03| 1.02| 0.50| 1.04| 0.05|
| Bal.     |    |    |     |     |    |    |    |    |       |

Table 3. Chemical composition of the casted bronze tuning fork.

| Elements | Cu | Sn | Zn | Pb  | Ni | Fe | Other |
|----------|----|----|----|-----|----|----|-------|
| [%]      |    |    |    | 2.03|    |    |       |
| Bal.     |    |    |    | 0.3 |    |    |       |

2.1. Acoustic tests

For material research regarding the sound damping capacity after pouring the three tuning forks from the studied materials, the studies was followed by a computer analysis of sound oscillograms produced by tapping.

To test the acoustic properties we have used the dedicated software called Analysis Center Version 2. Recording on the computer both amplitudes value and the time interval, we could calculate the damping capacity logarithmic decrement with the following expression:

\[ \delta = \frac{1}{t \cdot f} \ln \frac{A_i}{A} \]  

(1)

where:
- \( f \) = tuning fork oscillation frequency,
- \( t \) = oscillation time,
- \( A \) = initial amplitude,
- \( A_i \) = amplitude after a period of time \( t \).
In order to increase the measurement accuracy, has not been taken into consideration two successive amplitudes, but two amplitudes in a period of time. There were realized several oscillograms for each material at various impact intensities, and at different periods of time, the results being comparable. For illustration we present in figure 3 a, b, c, one oscillogram for each alloy with acoustic properties, based on which the logarithmic decrement was calculated.

\[ f = 1100 \text{ Hz}, \quad \delta = 5.42 \times 10^{-4} \]
\[ f = 1500 \text{ Hz}, \quad \delta = 9.94 \times 10^{-4} \]
\[ f = 1300 \text{ Hz}, \quad \delta = 6.32 \times 10^{-4} \]

**Figure 3.** Tuning forks oscillograms for: (a) white cast iron; (b) bronze; (c) aluminum; and their logarithmic decrement, \( f \) – frequency, \( \delta \)– vibration damping capacity.

### 2.2. Structural analysis

Characterization of material behavior at different tests must be made knowing particularities from structural point of view. In the following images are presented optical micrographs and scanning electron micrographs of the three types of materials used, EDX analysis on the surface and in line. In figure 4 are presented the optical micrographs for the three types of materials: bronze, aluminum, and white cast iron alloys.

**Figure 4.** Microstructures of the three types of alloys: (a) CuSn alloy for bells, (b) AlSi alloy with acoustic properties, (c) martensitic white cast iron.
From the bronze micrographs analysis two phases are highlighted: one solid solution $\alpha$, and a chemical compound $\epsilon$. The white cast iron, sectioned and analyzed at the half of the radius, presents a dendritical structure, with primary carbides, ledeburite, and martensite.

In figure 5 are presented SEM microscopies for the sample from the cast iron tuning fork. In figure 6 is presented the elements distribution in the section, at a 20 $\mu$m scale. Figure 7 presents individual element distribution map on sample surface.

**Figure 5.** The microstructure obtained from scanning electron microscopy (SEM):

- a) 100$\mu$m;
- b) 50$\mu$m;
- c) 20$\mu$m;
- d) 10 $\mu$m.

**Figure 6.** Elements distribution map for all the elements on the sample surface:

- a) SEM image for sample, 20 $\mu$m;
- b) distribution for all the elements on the surface

**Figure 7.** Individual element distribution map on sample surface

- a) C;
- b) Cr;
- c) Cu;
- d) Fe;
- e) Mn;
- f) Mo;
- g) Ni;
- h) Si.
Figure 8 and 9 presents the chemical EDX analysis in line in order to observe the variation on the chemical properties of the elements, as long as crossing the surface field with different structural elements of the material. The graphs indicates a significant variation of the Fe and Cr, the main elements form the elaborated alloy. Cr and Mn carbides are concentrated on the ledeburitic areas.

![Figure 8. In line analysis for white cast iron sample, on a 70 μm line length](image1)

![Figure 9. The analyzed area, prepared for the elements inline analysis](image2)

2.3. Mechanical tests

From the sound producing point of view (vibration), the elastic modulus must be as small as possible, so that at the lowest stress the deformation would be the highest.

Also in terms of elastic deformation dimension, necessary to produce oscillation, the material must have the highest elastic limit. Most materials that have a low elastic modulus have also a low elastic limit. In this case is more appropriate to appreciate the elastic property considering the elastic deformation energy when subjected to vibration [4].

The mechanical work (energy) of elastic deformations is the amount of mechanical work consumed by the action of external forces in order to deform an elastic body. Analyzing the stress-strain curve this value corresponds to the area between the curve and the strain axis. This feature would better appreciate the elastic characteristic of a material with acoustic properties [3].

The elastic property of a material subjected to low speeds stresses is different from the elastic property at high deformation speeds, and hence the need to assign other properties that characterize the elastic behavior for acoustic stresses [8].

The elastic modulus determined at low deformation speeds is considered independent of time, is called static modulus (Young's modulus) and is smaller than the modulus determined at high stress speeds. This difference arises due to a material relaxation phenomenon and therefore is called the relaxed elastic modulus.

The phenomenon of elastic modulus increasing along with the deformation speed leads to a shift of deformation versus the applied stress, meaning a delay in deformation. In the case of the oscillation, an outphasing angle between the stress and strain appears, thus producing a dissipation of deformation energy. Practically, the elastic imperfection is characterized by complex phenomena which take place within the material structure and result in an internal friction process characterized by energy consumption, leading to an oscillation damping process [5]. Internal friction is a particularly important property of materials used for the production and transmission of sounds [6].

The most important measurement that characterizes the material in terms of internal friction is the damping capacity logarithmic decrement, defined by the ratio between two consecutive amplitudes of a body subjected to free oscillation.

\[
\delta = \ln \frac{A_n}{A_{n+1}} \tag{2}
\]
where:
\( \delta \) - the damping capacity logarithmic decrement,
\( A_n \) - initial oscillation amplitude,
\( A_{n+1} \) - final oscillation amplitude.

There are also other methods for measuring the internal friction property, such as: the measurement of the energy consumption for maintaining oscillation, the measurement of the ratio between two frequencies adjacent to the resonant frequency, the measurement of the ratio between the static and dynamic elastic modulus etc [7].

In order to characterize the mechanical properties of the material, we performed traction tests for the three specimens of our materials, presented in figure 10. We used the testing machine Instron 8801. This is a compact servohydraulic fatigue testing system designed for both dynamic and static testing for materials and components.

For a strong grip in the machine, we used the hydraulic wedge grips. Each grip functions independently of the other, an external hydraulic supply providing pressure to both open and close the grips. When gripping pressure is applied, the relative vertical position of the specimen/jaw faces remains unchanged to prevent specimen load generation during the gripping process. Once the grip faces contact, the specimen the hydraulic pressure produces a vertical force on the grip head. The grip force will remain constant as the design automatically compensates for specimen thickness changes.

![Figure 10. Traction curve for the white cast iron-C2, aluminum and bronze alloys.](image)

Also for getting better results an 2620 series extensometer was used to record the strain. The flexural element is a special alloy operating beam with fatigue certified foil gauges bonded to it. The gauges are arranged in a fully active four-arm Wheatstone bridge circuit. It is mounted in a lightweight frame and accurately follows the strain amplitudes applied to it.

| Nr. crt. | Alloy | Elastic modulus \( E \) [daN/mm\(^2\)] | Yield point \( \sigma_{0.2} \) [daN/mm\(^2\)] | Unit energy \( W \) [daN/mm\(^2\)] |
|----------|-------|--------------------------------------|----------------------------------|-------------------|
| 1        | CuSn  | 4283                                 | 22                               | 0,056             |
| 2        | AlSi  | 8691                                 | 14,7                             | 0,012             |
| 3        | FeC   | 16000                                | 40                               | 0,050             |
where:

\[ W = \frac{\sigma_{0.2}^2}{2E} \]  

(3)

From this analysis results that the unitary alloy energy for the martensitic white cast iron is approximately the same than the same property of bronze, and for the aluminum alloy the energy is almost a quarter of the bronze and cast iron.

This component does not fully characterize the property of sound production and transmission by the analyzed material, and it must be correlated with the sound damping capacity, presented in.

3. Discussions
A material designed for acoustic applications, must possess, physically speaking, elastic properties characterized by:

- the smallest Young Modulus,
- the highest elastic limit (\( \sigma_{0.1}, \sigma_{0.2} \)),
- the smallest internal friction (\( \delta \)) and logarithmic decrement.
- the highest unit energy, \( W \).

Depending on the intended use of the object, the material with acoustic properties must meet other requirements. In case of piano resonance board: maintaining the elastic properties during time and preventing the loss of elastic properties by aging. In case of bells: maintaining the properties of impact resistance during time.

In addition to the elastic properties, in most cases, the materials intended for use in the acoustic field must meet other specific requirements.

The modulus of elasticity for iron is very high compared to the other two materials, aluminum and bronze, this is a disadvantage for producing sounds but, also due to the high yield strength, the unit energy for the cast iron is approximately equal to the bronze sample, and superior to that of aluminum (table 5). Another important factor in terms of sound analysis, logarithmic decrement of damping, is seen from the calculations that cast iron and bronze are very close, while aluminum is approximately twice as large, therefore unfavorable acoustic properties.

A surprising fact, that should be remembered, is in the bells construction domain, which is an acoustic device, where the use of alloys based on recipes from ancient times (the Bronze Age) is a reality fact, although there are iron-base alloys (developed in the actual Iron Age) that are much cheaper and with similar properties.

4. Conclusions
Correlation of mechanical properties (yield strength, modulus of elasticity) with the acoustic properties (energy unit, logarithmic decrement of damping) is imperative, especially because it seeks new materials, cheaper, easier to obtain and manufactured for sound production devices. Regarding acoustic properties martensitic white cast iron, in terms of its characteristics can become an interesting material. Even if the elastic modulus is very high compared to the other two materials, being unfavorable, however, the acoustic properties are comparable with those of dedicated bronze alloys for acoustic applications, due to the high yield strength. It is known from experimental studies that the structure of Fe-C alloy with the best elastic properties is troostite and upper bainite. In these circumstances, thermal treatment of martensitic white cast irons is a promising solution. Will follow the study of thermal treatments applied to optimize the sound properties and to obtain troostitic type structures with elastic properties that correspond to an optimum acoustic energy transmitted.

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