The Influence of Heat Treatment on the Phononic Multilayer Sensor

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In the work, the transmission of aperiodic quasi one-dimensional sensor built of $Zr_{55}Cu_{30}Ni_5Al_{10}$ amorphous alloy was tested using the Transfer Matrix Method algorithm. Transmission peak shifts were analyzed depending on the temperature of the flowing liquid. The influence of annealing in the temperatures 693K and 773K of the amorphous alloy on the structure of the sensor transmission bands was analyzed. The existence of bands in the examined structures has been shown. The best phononic properties were found in the structure heated to 773 K.

Keywords: phononic, transfer marix, aperiodic, multilayers, acoustic

Despite various physical grounds, the phenomena occurring during the propagation of electromagnetic and mechanical waves are similar to each other. For both types of waves, similar phenomena occur, such as the lack of propagation of waves of given frequencies in the analyzed structures (occurrence of a band gap). The properties of electromagnetic waves are examined for photonic structures [1-6], while mechanical waves are analyzed in phononic structures [7-15]. Depending on the application, one, two and three-dimensional phononic crystals are used and their properties depend on the geometrical structure and type of materials used in the composite [16]. Designed phononic crystals can be used to control the flow in fire acoustic devices [17] or as selective filters [18, 19].

Many of the studies focus on determining the band structure [20-23], but unfortunately it is not possible to determine it for distributions that do not have spatial periodicity. Numerically real structures can be simulated using the FDTD algorithm [9, 24, 25]. Quasi one-dimensional cases can be solved analytically using Transfer Matrix Method algorithm [9].

Transfer Matrix Method algorithm

The mechanical wave falls on the structure $P_{in}^{(+)}$, propagates inside it, after which part of the wave is transmitted $P_{out}^{(+)}$ and the rest is reflected $P_{in}^{(-)}$. $P_{out}^{(+)}$. is always zero. The *d* is the layer thickness.

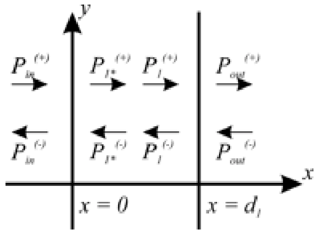

Fig. 1. Mechanical wave propagation in one layer structure.

The case of wave transmission in a single layer presented in Fig. 1 describes a system of equations

$$\begin{cases} \begin{bmatrix} P_{in}^+ \\ P_{in}^- \end{bmatrix} = \Phi_{in,1'} \begin{bmatrix} P_{1'}^+ \\ P_{1'}^- \end{bmatrix} \\ \begin{bmatrix} P_{1'}^+ \\ P_{1'}^- \end{bmatrix} = \Gamma_1 \begin{bmatrix} P_1^+ \\ P_1^- \end{bmatrix} \\ \begin{bmatrix} P_1^+ \\ P_1^- \end{bmatrix} = \Phi_{1,out} \begin{bmatrix} P_{out}^+ \\ P_{out}^- \end{bmatrix} \end{cases} \quad (1)$$

Occurring in Eq. (1) transmission matrix between the layers is defined as

$$\Phi_{i,i+1} = \frac{1}{2} \begin{bmatrix} \frac{Z_i + Z_{i+1}}{Z_i} & \frac{Z_{i+1} - Z_i}{Z_i} \\ \frac{Z_i - Z_{i+1}}{Z_i} & \frac{Z_i + Z_{i+1}}{Z_i} \end{bmatrix} \quad (2)$$

where Z_i is an acoustic impedance depending on the mass density ρ of *i* layer material and the mechanical waves propagation velocity *v*, determined by the dependence

$$Z_i = v_i \rho_i \quad (3)$$

The Z_i layer propagation matrix *i* is defined as

$$\Gamma_i = \begin{bmatrix} e^{ik_i d_i} & 0 \\ 0 & e^{-ik_i d_i} \end{bmatrix} \quad (4)$$

where the wave vector *k* for frequency *f* is given by

$$k_i = \frac{2\pi f}{v_i} \quad (5)$$

In the abbreviated form, Eq. (1) can be written as

$$\begin{bmatrix} P_{in}^+ \\ P_{in}^- \end{bmatrix} = \Phi_{in,1} \Gamma_1 \Phi_{1,out} \begin{bmatrix} P_{out}^+ \\ P_{out}^- \end{bmatrix} \quad (6)$$

Assuming that

$$M = \Phi_{in,1} \Gamma_1 \Phi_{1,out} \quad (7)$$

received

$$\begin{bmatrix} P_{in}^+ \\ P_{in}^- \end{bmatrix} = M \begin{bmatrix} P_{out}^+ \\ P_{out}^- \end{bmatrix} \quad (8)$$

M is called the characteristic matrix of the system and depends on the structure distribution and material properties of the composites components.

For *n* the number of layers, the characteristic matrix takes the form

$$\mathrm{M} = \Phi_{in,1} \Gamma_1 \Phi_{1,2} \Gamma_2 \Phi_{2,3} \Gamma_3 \Phi_{3,4} \Gamma_4 \Phi_{4,5} \cdots$$
$$\cdots \Phi_{n-2,n-1} \Gamma_{n-1} \Phi_{n-1,n} \Gamma_n \Phi_{n,out} \quad (9)$$

What can be written as

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$$M = \Phi_{in,1}\left[\prod_{i=2}^{n}\Phi_{i-1,i}\Gamma_i\right]\Phi_{n,out} \quad (10)$$

The transmission coefficient T can be determined from the characteristic matrix M

$$T = \left|\frac{1}{M_{1,1}}\right| \quad (11)$$

Analyzed structures and materials

The $A_{20}SA_{20}$ multilayer structure was analyzed in the work. The S is Severin structure [26], which for $L = 4$ is BBABBBABABABBBBAB. The A is distilled water and A_{20} means that it has a temperature of 20 degrees Celsius [27, 28]. Material B is $Zr_{55}Cu_{30}Ni_5Al_{10}$ amorphous alloy [29].

The speed of propagation of mechanical waves in distilled water (material A) depending on the temperature [27, 28] in the range from 10 to 55 degrees Celsius is described by the Eq. (12) and shown in Figure 2.

$$v(T) = 1{,}40238744 \cdot 10^3 + 5{,}03836171\,T - 5{,}81172916 \cdot 10^{-2}T^2 + 3{,}34638117 \cdot 10^{-4}T^3 - 1{,}48259672 \cdot 10^{-6}T^4 + 3{,}16585020 \cdot 10^{-9}T^5 \quad (12)$$

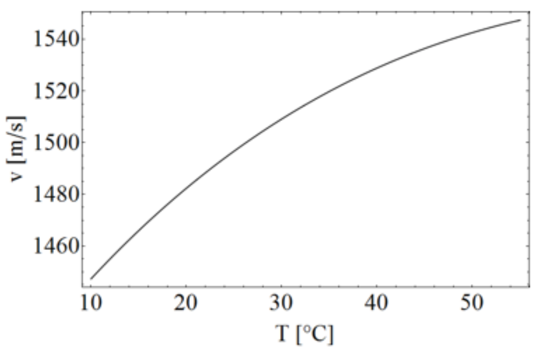

Fig. 2. Influence of temperature on the speed of propagation of mechanical waves in distilled water [27, 28]

Amorphous alloys due to their unique magnetic properties can be used as transformer cores [30-37]. However, the structure demonstrating the lack of long-range ordering exhibits interesting properties as a component for composite phononic structures [29].

The study investigated the influence of annealing of the $Zr_{55}Cu_{30}Ni_5Al_{10}$ amorphous alloy on the designed sensor transmission bands. The material parameters used are summarized in Table 1.

Results and discussions

In the work, was analyzed the transmission of a mechanical wave through a multilayer structure built of an amorphous alloy, between which distilled water flows with temperatures ranging from 10 to 55 degrees Celsius. The entire structure was immersed in distilled water at 20 degrees Celsius. Thicknesses of the layers have been selected so that the constructive interference inside the structure takes place. The tests were carried out for the amorphous alloy after solidification (Fig. 3a and 4a) and for samples heated for 10 min at 693K (Fig. 3b and 4b) and 773K (Fig. 3c and 4c). The tests were carried out for a water temperature of 20 degrees Celsius in the frequency range from 0 to 2 MHz (Fig. 3).

For the as quench and annealed in 693 K structures, the existence of two wide bandgap was found, while in the annealed sample at 773 K there were three bandgaps (Fig. 3). Then, for the frequency range from 850 kHz to 1150

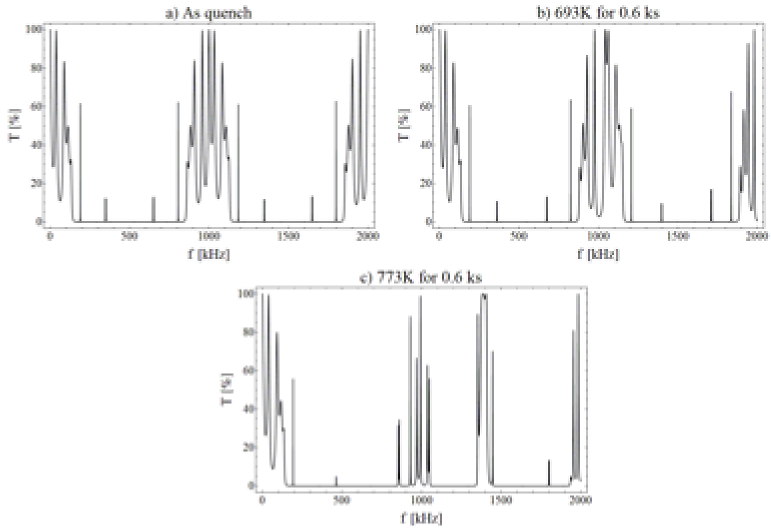

Fig. 3. Transmission of the analyzed structure for the amorphous alloy a) as quench and after 600 s in b) 693 K and c) 773K.

Table 1
MATERIAL PROPERTIES USED IN CALCULATIONS [27-29]

Material	Type	Mass density ρ [kg/m³]	Velocity of sound v [m/s]	Layer thickness d [μm]
$Zr_{55}Cu_{30}Ni_5Al_{10}$	As quench	6829	1633	816,5
	693K for 0.6 ks		1702	
	773K for 0.6 ks		2257	
Distilled water	20 °C	998	1482	750

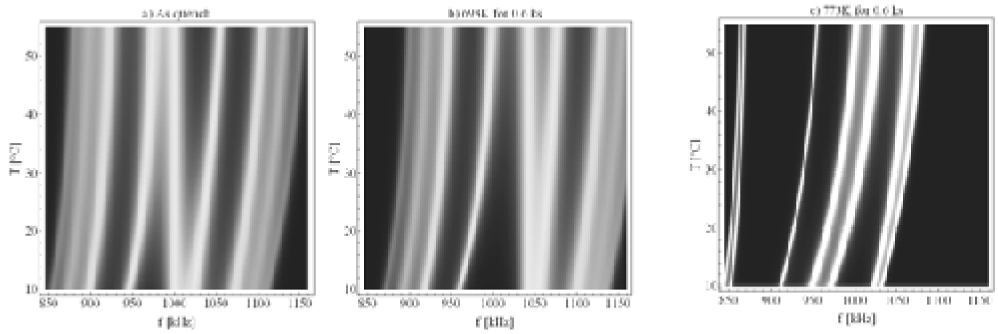

Fig. 4. Influence of distilled water temperature on transmission

kHz, the analysis of the influence of the water temperature inside the structure on the shifts of the transmission peaks was performed (Fig. 4). A small change in the mechanical wave propagation velocity between the base amorphous sample and annealed at 693 K caused non-linear shifts of temperature-dependent transmission peaks (Fig. 4a and 4b). The high value and small half-widths of the peaks for the sample after annealing at 773K in the most visible way reflect the relationship between the water temperature and the shifts of the transmission peaks.

After measuring the sensor, the shift of the transmission peaks allows to determine the fluid temperature.

Conclusions

The study investigated the effect of annealing a sensor constructed of a quasi one-dimensional aperiodic structure built of an amorphous alloy. The best properties for the detector with a frequency of about 1MHz showed a structure soaked at 773 K in 10 min. There were three bandgaps and high-speed peaks with a small half-width. The high sensitivity of ultrasonic sensors based on aperiodic structures allows, apart from determining the temperature, to show small admixtures to the base material.

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