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EXPERIMENTAL IDENTIFICATION OF THE MEASURE OF INTERNAL FRICTION IN PLATES WITH A TWO-DIMENSIONAL AUXETIC STRUCTURE

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Abstract: The analysis of relaxation processes occurring in metals, alloys and composites is an important problem of modern materials science. This paper presents the results of experiments to determine the measure of internal friction by impulse excitation technique (IET) in samples with different two-dimensional auxetic structures, namely, tetrachiral and re-entrant. IET is an advanced method for measuring material characteristics such as dynamic elastic and shear moduli, dynamic Poisson's ratio and internal friction to study deformation, softening, relaxation mechanisms and phase transformations in various materials. In the present research, five series of specimens of each structure have been made from photopolymer resin by sterlitography technology, which differ from each other in relative density. According to the test results, the dependence of internal friction on the sample density was determined. From the analysis of the obtained data, it was found that the re-entrant structure has a higher measure of internal friction, which indicates more pronounced viscoelastic properties, which in turn means a greater ability of the re-entrant structure to dampen the energy generated by the dynamic excitation. The values of the internal friction measure for the re-entrant structure at the peak point exceed the similar values for the tetrachiral structure by a factor of 6.44, in so doing with the increase in the relative density of the structure, the measure of the internal friction decreases irrespective of the type of the considered structures.

Keywords: Stereolithographic printing, tetrachiral honeycomb structure, re-entrant honeycomb structure, internal friction, impulse excitation technique

ЭКСПЕРИМЕНТАЛЬНОЕ ОПРЕДЕЛЕНИЕ МЕРЫ ВНУТРЕННЕГО ТРЕНИЯ В ПЛАСТИНКАХ С ДВУМЕРНОЙ АУКСЕТИЧЕСКОЙ СТРУКТУРОЙ

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Аннотация: Анализ релаксационных явлений, происходящих в металлах, сплавах и композитах, является важной проблемой современного материаловедения. В данной статье представлены результаты экспериментов по определению меры внутреннего трения по технике импульсного возбуждения (IET) в образцах с различной двумерной ауксетической структурой, а именно тетракиральной и повторно-входящей. IET – это продвинутый метод измерения таких характеристик материалов, как динамические модули упругости и сдвига, динамический коэффициент Пуассона и внутреннее трение, для исследования процессов деформации, разупрочнения, механизмов релаксации и фазовых превращений в различных материалах. Образцы изготавливаются по технологии стерлитографии из фотополимерной смолы. Авторами были испытаны по пять серий образцов каждой структуры, которые отличаются между собой относительной плотностью. По результатам испытаний определена зависимость внутреннего трения от плотности образца. Из анализа полученных данных установлено, что повторно-входящая структура обладает более высокой мерой внутреннего трения что говорит о более выраженных вязкоупругих свойствах, что в свою очередь означает о большей способности повторно-входящей структуры гасить энергию, возникающую при динамическом воздействии. Значения меры внутреннего трения для повторно-входящей структуры в пиковой точке превышает аналогичные значения для тетракиральной структуры в 6.44 раза.

При этом с увеличением относительной плотности структуры мера внутреннего трения уменьшается независимо от вида рассмотренных структур.

Ключевые слова: Стереолитографическая печать, тетракиральная сотовая структура, повторно-входящая сотовая структура, внутреннее трение, метод импульсного возбуждения

1. INTRODUCTION

The analysis of relaxation phenomena occurring in metals, alloys and composites is an important problem of modern materials science. The results obtained as a result of such studies provide extensive information on the kinetics of crystal structure defects and allow one to predict the behaviour of structural elements made of these materials under various operating conditions. For the phenomenological description of relaxation processes in materials subjected to sufficiently weak external excitation, which is not reduced to plastic deformations, the hereditary theory of elasticity is usually adopted.

Recent trends are aimed at a wider use of fractional derivatives and other fractional operators in hereditary models of viscoelasticity, a detailed review of which could be found in [1-4]. In the last two decades, various fractional calculus models have also been widely used to describe the rheological properties of various building materials such as concrete [5, 8, 9, 10], asphalt [11, 12] and bituminous [13, 14] mixtures, asphalt concrete [15, 16], polymer concrete [17], rubber concrete [18], fibrocomposites [18, 19], polymer foams [20] and polyurethanes [21]. In this case, the order of the fractional derivative, or the so-called fractional parameter, is an additional microstructural characteristic of the material describing the level of its viscosity and microstructural changes [22], and for solid materials it varies from 0 (corresponding to a purely elastic material) to 1 (corresponding to a material described by the traditional viscoelastic model).

Fractional calculus models are nowadays widely applied in materials science, rheology and mechanics not only because they allow one to describe a whole range of dissipative mechanisms (including creep and relaxation phenomena [3, 4, 11]). with fewer parameters compared to traditional rheological formulations involving time derivatives of a whole order [17]. The fractional parameter variation could also allow one to account for a wide range of other important properties occurring over time in materials, such as ageing effects [19], chloride resistance of concrete and others. composites and their cohesion [9], concrete fracture [5], internal friction [10, 20], the phenomenon of second, or volume, relaxation [3, 10], which should be considered together with the first, or shear, relaxation for advanced composite materials, and would also enable modelling the properties of viscoelastic materials with negative Poisson's ratios [3, 23], which are called auxetics.

In order to incorporate fractional calculus models into engineering applications, it is necessary to define their characteristics [12, 21, 24-26], in particular the orders of fractional operators, for real structural materials, and/or structural elements, and/or engineering structures. The fractional parameter is of great interest not only from a computational but also from a physical point of view.

Several methods for fractional parameter estimation have been proposed, and the majority of them are based on quasi-static experimental tests such as pre-peak steady bending tests [5], uniaxial dynamic modulus tests [16]. creep tests [8, 24], stress relaxation tests [20, 24], and three-point bending tests of beams [12, 15]. While minimizing the errors between the numerical model and measurements provides the opportunity to estimate the material model parameters by analyzing the behaviour of materials to impulsive loading over a long period of

time [25], dynamic methods take the response to variable loading into account. According to [26], dynamic methods could be referred to Dynamic Mechanical Analysis (DMA) [14, 19] based on the measurement of amplitude and lag in the stress-strain relationship caused by oscillating force, vibration testing [26] and Impulse Excitation Technique (IET) [27] based on the measurement of resonant frequencies during shock excitation, allowing the evaluation of damping characteristics [28]. Using numerical modelling of experimental data from external vibration studies of suspension bridges, which led to the analysis of the model using the fast Fourier transform, a fractional parameter identification procedure was proposed in [29], allowing the authors to obtain damping coefficients dependent on natural frequencies of vibrations.
There are several ways to measure internal friction in different materials. Pavlova et al. [4] measured damping as the logarithmic damping of oscillations of an inverted torsion pendulum

$$Q^{-1}=\frac{1}{\pi n}\ \ln\frac{A_i}{A_{i+n}}, \tag{1}$$

where A_i and A_{i+n} are the amplitudes of the i-th and (i+n)-th periods of vibrations, respectively.
Recently, devices capable of direct measuring the internal friction in different materials have been proposed. Huang et al. [6] used a DTM-II-J dynamic elastic modulus internal friction analyzer manufactured by Hunan Zhenhua Analysis Instrument Co. Ltd., China. The device is based on the bending resonance method according to GB/T13665-2007 [7].
The principle of the bending resonance method is as follows: the frequency is increased until the strain amplitude reaches half of the resonance value, which corresponds to the frequency ω_2 and the period T_2. When the frequency is decreased until the strain amplitude reaches half of the resonance value, this frequency is denoted as ω_1, and the period as T_1. In so doing, $\Delta\omega$ is the difference value of $\omega_2-\omega_1$, and ΔT is the difference value of T_2-T_1. Then the damping could be evaluated as

$$Q^{-1}=\frac{|\Delta\omega|}{\sqrt{3}\omega_r}=\frac{|\omega_2-\omega_1|}{\sqrt{3}\omega_r}, \tag{2}$$

or

$$Q^{-1}=T_r\frac{|\Delta T|}{\sqrt{3T_2T_1}}=T_r\frac{|T_2-T_1|}{\sqrt{3T_2T_1}}, \tag{3}$$

where ω_r is the resonant frequency, and T_r is the resonant period [6].
The current study is focused on the experimental detection of the measure of internal friction of a metamaterial with a two-dimensional auxetic structure. For this purpose, plates with two different honeycomb structures would be considered, namely: tetrachiral and re-entrant. Auxetics have several advantages over conventional materials, among them, increased energy dissipation, increased resistance to crack formation and opening, better resistance to indentation. In this study, the effect of such factors as the internal dimensions of the honeycomb filler on the internal friction and fractional parameter would be investigated for metamaterials using a resonant frequency and damping analyzer (RFDA Basic) implementing the impulse excitation technique (IET) [27, 28].

2. MATERIALS AND METHODS

2.1. Materials for experiment

Samples for the study are made by additive manufacturing using Formlabs Form 3 3D printer. Formlabs Clear photopolymer resin with the following characteristics is used for manufacturing: tensile strength σ_t = 65 MPa, tensile modulus E_t = 2.8 GPa, and flexural modulus E_f = 2.2 GPa. This resin is transparent, what

provides good quality control of the manufactured samples.

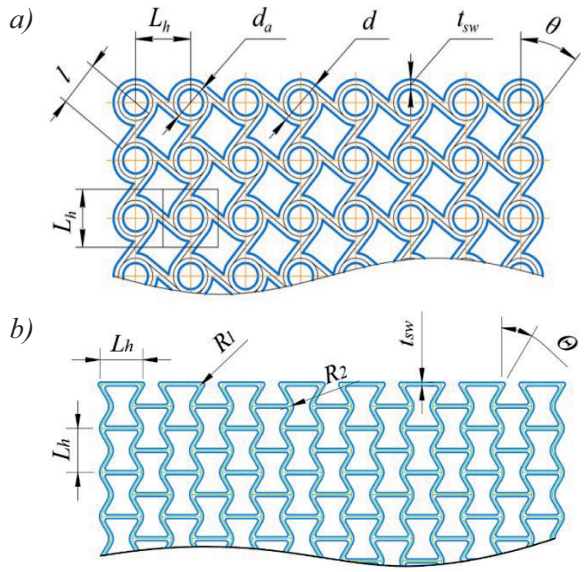


Figure 1. Type of tested structures: (a) tetrachiral (b) re-entrant

For laboratory experiments, samples of tetrachiral structure (Figures 1a, 2a) and re-entrant structure (Figures 1b, 2b) were produced, the geometrical parameters of which are given in Table 1. The variable parameter is the relative density of the cell:

$$\rho = A_{str}/A, \tag{4}$$

where A_{str} is the amount of material used to manufacture the structure, and A is the amount of material required to manufacture a full-body plate of the same dimensions.

Five series of samples for each honeycomb structure were designed.

The production of specimens includes the following steps:

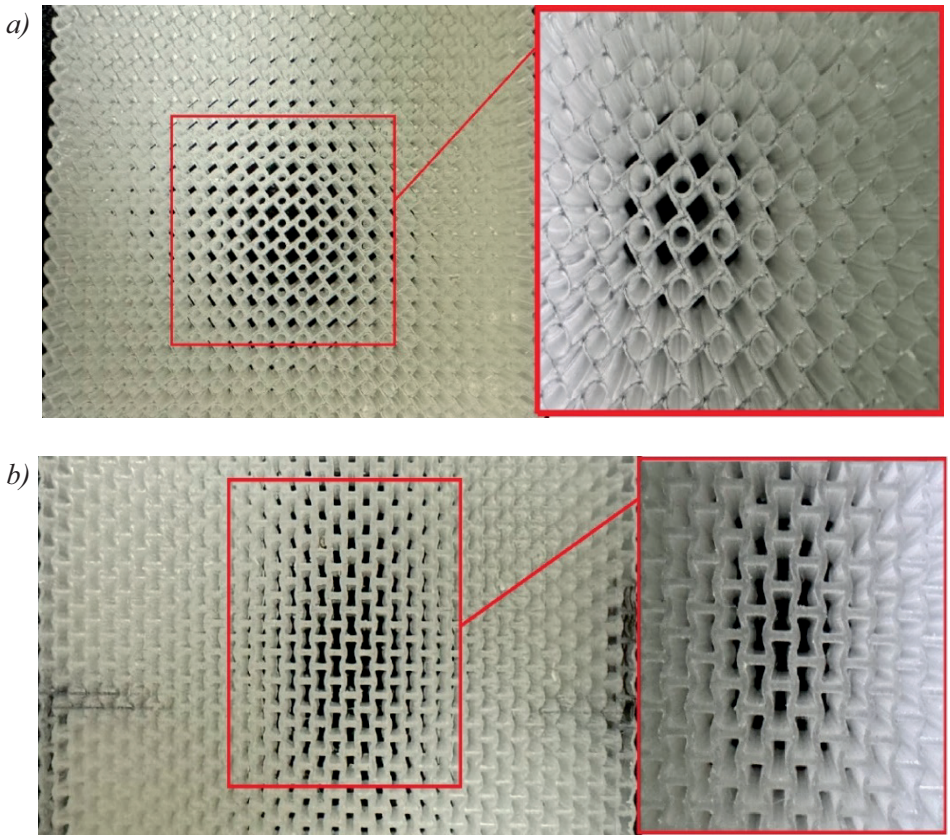


Figure 2. General view of produced samples: (a) tetrachiral (b) re-entrant

Table 1. Geometrical parameters of the samples.

Relative density ρ, %	l, mm	L_h, mm	d_a, mm	d, mm	t_{sw}, mm	R_1, mm	R_2, mm	Θ, ^{o}
Tetrachiral structure								
14	1.6227	2.08	1.3	1.3541	0.1082	-	-	20
21.1	1.6227	2.08	1.3	0.08485	0.1697	-	-	20
28.2	1.6227	2.08	1.3	0.11775	0.2355	-	-	20
35.3	1.6227	2.08	1.3	0.1529	0.3058	-	-	20
42.4	1.6227	2.08	1.3	0.19085	0.3817	-	-	20
Re-entrant structure								
14	-	1.97	-	-	0.1082	0.1	0.5	30
21.1	-	1.97	-	-	0.1697	0.1	0.5	30
28.2	-	1.97	-	-	0.2355	0.1	0.5	30
35.3	-	1.97	-	-	0.3058	0.1	0.5	30
42.4	-	1.97	-	-	0.3817	0.1	0.5	30

1. Printing the honeycomb structures on a 3D printer;
2. Cleaning the printed elements in an ultrasonic bath using isopropyl alcohol;
3. Pre-curing in an ultraviolet chamber;
4. Bringing the honeycomb structures to the required dimensions and surface flatness by grinding;
5. Cleaning of the ground elements from dust;
6. Final curing of the samples in an ultraviolet chamber.

2.2. Impulse excitation method

In this work, internal friction measurements were performed using the Impulse Excitation Technique (IET). The Impulse Excitation Technique (IET) is an advanced method for measuring material characteristics such as dynamic elastic and shear moduli, dynamic Poisson's ratio and internal friction to investigate deformation, softening, relaxation mechanisms and phase transformations in various materials. Experimental studies can be carried out both at room and high temperatures.

The method is based on the following. A specimen of a strictly defined shape and dimensions is freely rested on a wire support (Figure 3). The contact between the wire and the surface of the specimen must be established at certain points, so-called nodes. The location of the support plays a key role in the measurement of internal friction. If the support points do not coincide with the nodes, the internal friction will be significantly increased. In such a situation, the damping is generated not by the material but by the test machine.

The position of nodes is calculated separately for each sample shape with specific dimensions. After a small impact on the sample, it starts to vibrate. The signal is picked up by a microphone and transmitted to a personal computer, where the Resonant Frequency and Damping Analyzer (RFDA) software performs a Fast Fourier Transform (FFT), in order to calculate resonant frequencies, dynamic elastic and shear moduli, dynamic Poisson's ratio, damping factor, and internal friction.

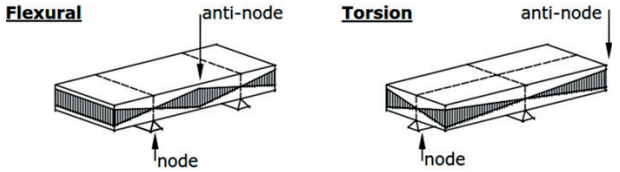


Figure 3. Schemes of bending and torsional vibrations of rectangular rods

For this experiment, specimens with dimensions l = 10 cm, b = 5 cm, t = 1 cm were produced. The RFDA Basic program obtained nodes at a distance of ≈22.54 mm from the edge

of the plate. Then the specimens were mounted on wire supports located at the distance of ≈54.92 mm from each other. After that a metal ball attached to a flexible rod was used to impact the plates. Figure 4 shows a photo of the experiment to determine the internal friction of the plates. Figure 5 shows the window of the initial data.

Internal friction is characterized by the following relationship:

$$Q^{-1} = \frac{k}{\pi \omega_r}, \tag{5}$$

where k is the damping coefficient (the inverse of the relaxation time).



Figure 4. Process of the experiment to determine the internal friction.

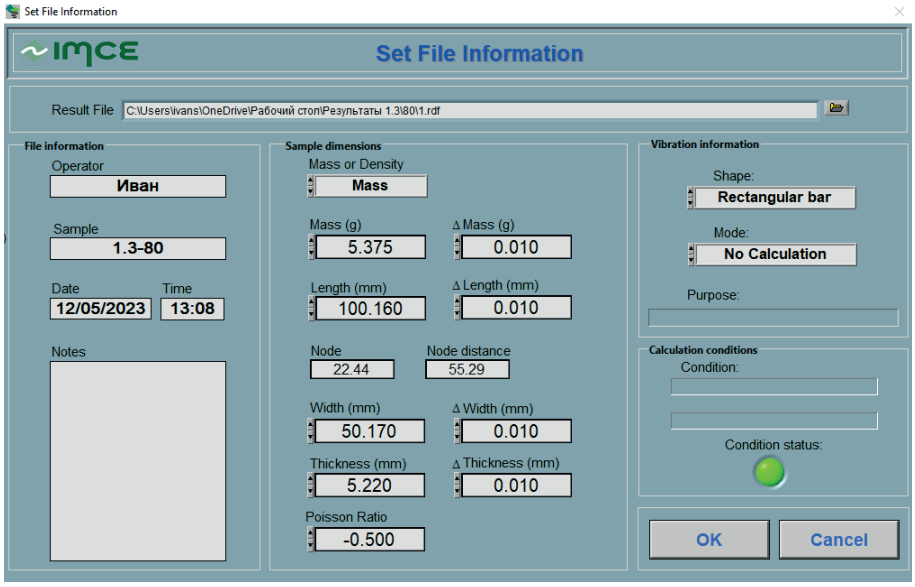


Figure 5. Input data task screen

3. RESULTS

According to the test results, the data necessary for calculations according to formula (5) were obtained, which are given in Tables 2 and 3, and the graph of internal friction dependence on the relative density of a honeycomb filler was plotted (Figure 6).

Table 2. Results of damping tests of tetrachiral structure

Relative density ρ, %	k, c^{-1}	ω_r, Hz	Q^{-1}
14	5.07	38.50	0.0487
21.1	7.18	39.05	0.0528
28.2	5.80	44.19	0.0434
35.3	280.86	12178.94	0.0073
42.4	251.35	11622.32	0.0069

Table 3. Results of damping tests of re-entrant structure

Relative density ρ, %	k, c^{-1}	ω_r, Hz	Q^{-1}
14	15.68	20.31	0.24
21.1	23.05	21.76	0.34
28.2	15.22	22.20	0.22
35.3	14.90	22.13	0.21
42.4	13.18	22.22	0.19

From the analysis of the graphs in Figure 6, it could be seen that the re-entrant structure has a higher measure of internal friction, which indicates more pronounced viscoelastic properties, what, in its turn, means that the re-entrant structure has a greater ability to dissipate the energy arising from the dynamic action. It is observed in both graphs that the highest internal friction is exhibited by the second set of samples with the relative density of 21.1%. In the tetrachiral structure with relative density greater than 35.3%, the measure of internal friction becomes close to 0, resulting in the decrease of the auxetic properties in structures with this relative density. However, in the re-entrant structures the values of Q^{-1}, although it goes to decrease after the relative density value of 28.2%, remain at a rather high level. The values of the measure of internal friction for the re-entrant structure at the peak point exceed the same values for the tetrachiral structure by a factor of 6.44.

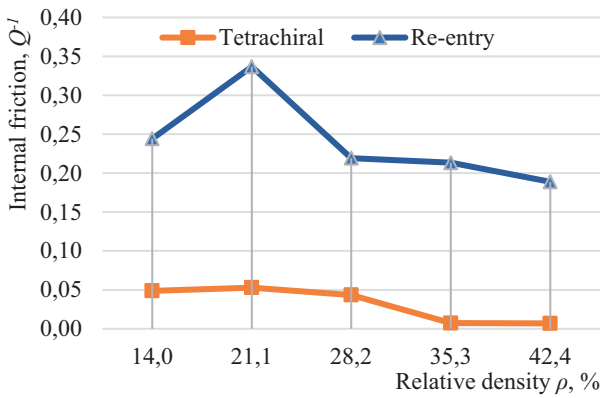


Figure 6. Graph of the dependence of internal friction on the relative density of honeycomb

4. CONCLUSION

The authors have validated the impulse excitation technique for non-destructive analysis of viscoelastic properties of metamaterials with two-dimensional auxetic structures. The following conclusions could be formulated:

1. the re-entrant structure has more pronounced viscoelastic properties compared to the tetrachiral structure;
2. as the relative density of the structure increases, the measure of internal friction decreases independent of the type of the considered structures;
3. the use of the impulse excitation method enables preliminary estimation of the damping properties of the selected honeycomb structures;
4. according to the results obtained it could be deduced that these plates are not pure elastic, but are viscoelastic, and it is recommended to apply the standard linear solid body model with fractional derivatives to describe the mechanical behaviour of such honeycomb plates.

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