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Viscoelastic Properties of Filled Polyurethane Auxetics

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The paper presents experimental values of longitudinal and transverse transmission ultrasonic waves speed and their absorbance coefficient obtained with the help of discrete immersed method in metal filled polymer auxetic samples with polyurethane matrix. Poisson's ratio, real and imaginary parts of complex dynamic elastic modulus (Young's modulus, shear modulus, bulk modulus) and mechanical losses tangent of angle for longitudinal, transverse and bulk deformation have been calculated regarding paper's results. Viscoelastic properties of polyurethane auxetic have been examined regarding different theoretical approaches. To support negative values of Poisson's ratio, a filled polymer model with critical filler amount and auxetic deformation models have been used. Models structural characteristics for filled polyurethane auxetics have been defined. Systems modeling with solid bulky inclusions, that are able to absorb and to disseminate ultrasonic waves, enables to consider suchlike systems as complex density materials. It is shown that in certain ratio of wave parameters and environment structural and mechanical properties, resonance effects take place, regarding filler's particles vibration as inclusions in general.

Keywords: polymer auxetic, longitudinal and transverse ultrasonic waves, Poisson's ratio, viscoelastic Young's modulus, mechanical loss tangent of angle, complex density structure, resonance effect.

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Introduction

Nowadays researches are highly interested in methods that enable to increase operation properties of traditional materials by creating structures that possess nonlinear and abnormal distortion properties, up to the point of obtaining adaptive physical reaction of the materials to the external influence [1]. Auxetics, materials with negative Poisson's ratio, can be regarded as abnormities.

Great majority of research papers are dedicated to auxetics investigation. Research paper [2], to be precise, presents materials' overview that can be considered as natural, polymer, composite and textile auxetics; investigates their structural properties according to geometric approach as well as their reaction and behavior in physics fields of force. Special aspects of auxetics structure formation, fillers route and influence on them are considered in [3], along with examining their properties that have been governed regarding set analytical models. The research paper represents structure elements reaction that leads to Poisson's ratio change in dependence of regulations and auxetic composite properties. Research paper [4] regards interactive methods in modeling auxetic structures. It assumes metamaterials and auxetics structure, geometric and numeric records of configurative elements, structuring modification and form alternation. Taking into account references [5], becomes clear that auxetic materials abnormal properties are realized through microscopic models.

Nanomaterials also possess auxetic properties. Experimental approach and modeling [6] assert that nanocrystal structures, materials with carboniferous nanotubes, graphene, metal nanoplastic, borofen, pentagraphen possess negative Poisson's ratio while deformation. Fullerite C_{60} auxetic properties are

investigated in paper [7]. For the following auxetic structure Gruneisen Parameter, Debye temperature and heat absorptive capacities (transmission, current, intermolecular, inner molecular) are set.

Investigating properties of auxetic materials reveals their potential in different spheres of science, engineering and human livelihood [8]. Auxetic materials are used and can be employed as energy absorption matter, intelligent screens, protective means, and detectors in control systems [9] in navigation and aviation [10]. Research overview [11] proves implementation of auxetic materials in sport, and paper [12] shows how to use them both in architecture programs and in searching new architecture forms.

Polymer auxetics play a major role among materials with negative Poisson's ratio [13-15]. Polymer auxetics are applied in various spheres [16] such as engineering and medicine, where need exists in employing smart and highly efficient materials. That sort of auxetics polymer materials combine high stiffness and durability with considerable savings in weight, corrosion resistance, chemical endurance and expenses decrease. Auxetics polymer materials are of great importance for different branches of engineering, science, biomedicine engineering and for many manufacturing industries as well, including aerospace and defense (A&D) industry. Sufficient progress in modeling auxetic properties and structure of polymer systems with negative Poisson's ratio has been achieved in last few years [17-19].

Polyurethane auxetics polymer systems play important part among auxetics polymer materials [20]. Research paper [21] presents brand new method of obtaining auxetic polyurethane foam that is marked by low glass-transition temperature though is still thermostable. Polyurethane auxetic investigation [22, 23] proves potentiality of transmission from auxetic state to normal condition and vice versa, also aspects of hysteresis phenomena and nonlinear distortion. Investigations of various polyurethane auxetics as a result of different experimental approaches [24, 25] demonstrate that for such systems Poisson's ratio changers in -0.1 to -1. Paper [26] shows that for obtained anisotropy polyurethane foam Poisson's ratio is above 1 and ratio rating of longitudinal and transverse stiffnesses exceeds 50.

Purpose of the paper is investigation of auxetic polyurethane composites viscoelastic properties and their treatment with reference to modeling structure formation processes.

I. Materials and Investigation Methods

Thermoplastic polyurethane (TPU) that was synthesized from 4.4'-Methylen diphenyl diisocyanate, 1,4-Butanediol and Polytetramethylene ether glycol with molecular weight 1500 have been investigated. High dispersed powders of iron (Fe), molybdenum (Mo) and wolfram (W) with particles' radius 0.3-1.0 μm were used as fillers. Filled polymer systems were obtained with the help of hot pressing in T-p mode just after the components were all mixed. Volume filler's density for TPU systems was critical to the system, so respectively for Mo, Fe, W it was 48, 43 and 52 % [27, 28].

Composites were obtained by mixing in TP-mode. Investigation samples were prepared as cylinders with diameter $D \cong 35$ mm and thickness $d_0 = 7$ - 9 mm. Samples' geometrical dimensions were checked with the help of micrometer. Parallel alignment of cylinder bases was checked in 5 different points, d_0 value was averaged due to the measurements.

Polymer materials density ρ was determined by hydrostatic weighting, measurement tolerance does not exceed 0.3 %.

Ultrasonic methods implementation is based on connections between polymer structure and its viscoelastic dynamic properties, i.e. Young's modulus and viscous friction. Ultrasonic methods advantage is that they afford possibility to investigate heterogeneous system's field of force, which stipulates ultrasound velocity, acoustic reduction, kinetics and dynamics of structural units, and to obtain data of inner material structure without its destruction.

Basis operation of the pilot unit, that operates polymer structure acoustic parameters, is specified in the paper [29, 30].

The pilot unit performance is based on going longitudinal and transverse ultrasonic waves through the sample that is merged into immersive liquid. Condition of agreeable interaction between liquid and sample in most cases is done automatically. Ultrasonic waves transmission surrounding in a ditch is silicon oil PFMS-4^{tm}.

The pilot unit consists of a ditch (Fig. 1), electronic module and PC for visualization and data manipulation.

In the ditch (1), made of fiberglass laminate, there are metal holders (2, 3) that are fixed still in certain position, where two Murata MA300D-1 ultrasonic transformers are set: one operates as oscillator (4) the other as a receiver (5). There is a stepper motor (7) under the ditch fixed with the help of special clips (6). Investigated sample (10) is put into appropriate holder (9) that is on motor shaft (8). When shaft axis, which is vertical to ultrasonic wave transmission vector, moves, longitudinal and transverse vibrations appear. In cases when angle of wave incidence on the sample with exactly parallel surfaces is zero, only longitudinal transmission takes place. If angle of rotation increase happens, both longitudinal and transverse transmission will take place in the sample. When reaching critical angle θ_{cr} (Brewster's angle), there will be longitudinal transmission on the sample's surface whereas transverse transmission in the sample itself.

The pilot unit permits to investigate longitudinal υ_l and transverse υ_t transmission at the same time, as well as rates their decay α_l and α_t at frequency $\omega = 1.884$ MHz.

Longitudinal transmission ultrasonic wave speed based on comparison of direct time determination results of initial pulse indication through immersed liquid at samples absence (τ) and presence (τ_l) between oscillator and receiver. If difference between the ranges is specified $\Delta\tau_l$ ($\Delta\tau_l = \tau - \tau_l$), value υ_l is determined by ratio:

$$\upsilon_l = \frac{\upsilon_{il} d_0}{d_0 - \Delta\tau_l \upsilon_{il}}, \quad (1)$$

where υ_{il} – ultrasonic wave speed transmission in immersed liquid; d_0 – sample's material thickness with exactly parallel surfaces. υ_t value is calculated according to ration:

$$\upsilon_t = \frac{\upsilon_{il}}{\sqrt{\sin^2(\theta_{cr.}) + \left(\cos(\theta_{cr.}) - \frac{\upsilon_{il}\Delta\tau_t}{d_0}\right)^2}}, \quad (2)$$

where $\Delta\tau_t$ – time difference between initial pulse indication transmission at sample's absence and its presence (τ_t), put at critical angle θ_{cr} towards line of dip.

When υ_l and υ_t data are specified, Poisson's ratio of polymer auxetic is calculated by ratio [27]:

$$\nu = \frac{2 - \left(\frac{\upsilon_l}{\upsilon_t}\right)^2}{2\left(1 - \left(\frac{\upsilon_l}{\upsilon_t}\right)^2\right)}. \quad (3)$$

Values α_l and α_t are determined as following:

$$\alpha_l = \frac{1}{d_0} \ln \frac{A_0}{A_l}, \quad (4)$$

$$\alpha_t = \frac{\sqrt{\upsilon_t^2 - \upsilon_{il}^2 \sin^2(\theta_{cr})}}{\upsilon_t d_0} \ln \frac{A_0}{A_t}, \quad (5)$$

where A_0 – ultrasonic wave initial pulse indication amplitude in signal receiver with sample's absence; $A_{l,t}$ – longitudinal (transverse) ultrasonic wave initial pulse indication amplitude in signal receiver after wave transmission through the sample.

υ_l and υ_t measurement tolerance does not exceed 5 m/s for α_l and α_t – 0.5 Np/m.

Measurements results of density, ultrasonic wave transmission, Poisson's ratio and absorbance coefficient in TPU-systems are presented in Table 1.

II. Results and Their Evaluation

As rates of decay in longitudinal and transverse ultrasonic waves are nonzero, complex Young's modulus E and μ were determined for polyurethane auxetics. Real (E', μ′) and imaginary parts (E'', μ″) of complex modulus were calculated according to the ratios:

$$E' = \rho\upsilon_l^2 \frac{1 - \frac{\alpha_l^2 \upsilon_l^2}{\omega^2}}{\left(1 + \frac{\alpha_l^2 \upsilon_l^2}{\omega^2}\right)^2}, \quad (6)$$

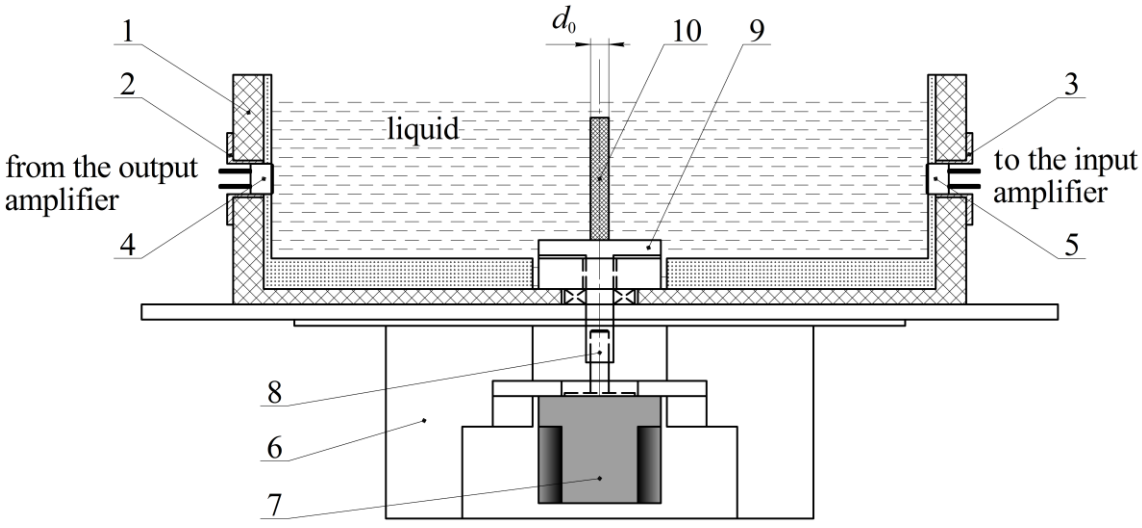

Fig. 1. Ditch scheme.

Table 1

TPU-systems density, ultrasonic waves transmission, Poisson's and absorption ratios

Material	ρ, kg/m^3	υ_l, m/s	υ_t, m/s	α_l, Np/m	α_t, Np/m	ν
TPU	1107	1635	1415	36	197	–1
TPU + W	9888	1775	1370	28	155	–0.24
TPU + Fe	3642	1750	1395	31	174	–0.37
TPU + Mo	4603	1755	1405	32	187	–0.39

$$E'' = \rho \upsilon_l^2 \frac{\frac{2\alpha_l \upsilon_l}{\omega}}{\left(1+\frac{\alpha_l^2 \upsilon_l^2}{\omega^2}\right)^2}, \quad (7)$$

$$\mu' = \rho \upsilon_t^2 \frac{1-\frac{\alpha_t^2 \upsilon_t^2}{\omega^2}}{\left(1+\frac{\alpha_t^2 \upsilon_t^2}{\omega^2}\right)^2}, \quad (8)$$

$$\mu'' = \rho \upsilon_t^2 \frac{\frac{2\alpha_t \upsilon_t}{\omega}}{\left(1+\frac{\alpha_t^2 \upsilon_t^2}{\omega^2}\right)^2}, \quad (9)$$

where ρ – density of polymer composite material; ω – ultrasonic wave circular frequency; α_l and α_t – absorbance coefficient of longitudinal and transverse ultrasonic waves.

If E', E'' and μ′ та μ″ are specified, real (k') and imaginary (k'') parts of bulk modulus (k) can be determined:

$$k' = E' - \frac{4}{3}\mu', \quad (10)$$

$$k'' = E'' - \frac{4}{3}\mu'' \quad (11)$$

Analysis of complex modulus, their real (E, μ) and imaginary (E', μ′) parts, that is presented in Table 2, indicates that their values are determined by metal filler critical amount in auxetic polymer matrix. Viscoelastic modulus crest values are appropriate for polyurethane systems filled with W. It is determined by filler's contribution to viscoelastic properties of polymer auxetics. Polyurethane systems auxetic properties are represented in bulk modulus. Imaginary parts k negative values of complex modulus should be marked for every TPU-system.

In classical theory of elasticity, shear deformation modulusμ, complex bulk modulus k and Lame coefficient λ were determined through E according to the ratio:

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)};\ \mu = \frac{E}{2(1+\nu)};\ k = \frac{E}{3(1-2\nu)}. \quad (12)$$

Carried calculations for not filled polymer in classical theory of elasticity mark that values μ and λ are infinitely large. Lame coefficient is negative for metal filled TPU (Table 3), μ and k values are a bit smaller in reference to those obtained during the experiment.

Table 2

TPU-system dynamic elastic modulus

Characteristic	Material			
	TPU	TPU + W	TPU + Fe	TPU + Mo
$E'\cdot10^{-9}$, N/m^2	2.95	31.07	11.12	14.14
$E''\cdot10^{-8}$, N/m^2	1.85	16.41	6.41	8.43
$tg\delta_E$	0.063	0.052	0.058	0.060
$\mu'\cdot10^{-9}$, N/m^2	2.08	17.86	6.74	8.58
$\mu''\cdot10^{-8}$, N/m^2	6.28	40.78	17.66	24.42
$tg\delta_\mu$	0.302	0.228	0.262	0.288
$k'\cdot10^{-9}$, N/m^2	1.82	7.26	2.13	2.69
$k''\cdot10^{-8}$, N/m^2	–6.53	–37.96	–17.14	–24.13
$tg\delta_k$	–0.359	–0.523	–0.804	–0.897
$E\cdot10^{-9}$, N/m^2	2.96	31.11	11.14	14.17
$\mu\cdot10^{-9}$, N/m^2	2.17	18.32	6.97	8.92
$k\cdot10^{-9}$, N/m^2	1.93	8.19	2.73	3.61

Table 3

Calculated TPU-systems viscoelastic values

Characteristic	Material			
	TPU	TPU + W	TPU + Fe	TPU + Mo
(12) $\mu\cdot10^{-9}$, N/m^2	∞	20.46	8.84	11.61
(12) $k\cdot10^{-9}$, N/m^2	0.33	7.01	2.13	2.65
(12) $\lambda\cdot10^{-9}$, N/m^2	∞	–6.64	–3.76	–5.08
(13) $E\cdot10^{-9}$, N/m^2	0	27.92	8.78	10.88
(13) $k\cdot10^{-9}$, N/m^2	0	6.29	1.68	2.04
(13) $\lambda\cdot10^{-9}$, N/m^2	–1.45	–5.96	–2.96	–3.91

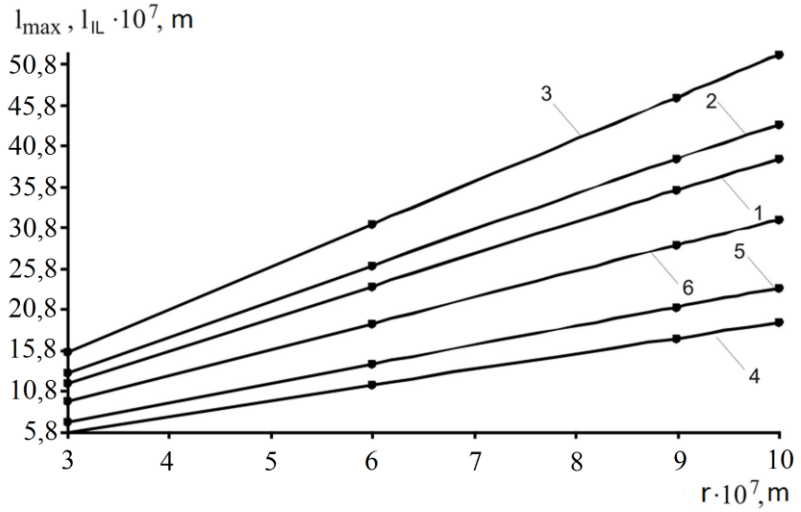

Fig. 2. Dependence of l_{max} (1-3) and l_{IL} (4-6) on r for TPU-systems: 1, 4 – TPU+52 vol.% Fe; 2, 5 – TPU+43 vol.% Mo; 3, 6 – TPU+48 vol.% W.

Another time Lame coefficient and related modulus with values $\mu > 0$, $\nu < 0$ for auxetic isotropic materials were determined. In this case, concerning μ modulus as major characteristic for TPU-systems we shall get the following:

$$\lambda = \frac{2\nu\mu}{(1-2\nu)};\ E = 2(1+\nu)\mu;\ k = \frac{2(1+\nu)\mu}{3(1-2\nu)}. \quad (13)$$

Calculated values of E and k modulus (table 3) equal 0 and differ greatly from TPU experimental data. For other PU-systems, theoretical and experimental difference in E value is 15 - 30 % and in k is 23 - 44 % accordingly. Lame coefficient value is negative conforming to the equation. Such difference between theoretical and experimental values of auxetic systems viscoelastic modulus stems from nonlinear deformation theory [31].

$E'(E'')$, $\mu'(\mu'')$ and $k'(k'')$ values enable to calculate mechanical losses tangent of angle for longitudinal, transverse and bulk deformation (Table 2):

$$tg\delta_E = \frac{E''}{E'}, \quad (14)$$

$$tg\delta_\mu = \frac{\mu''}{\mu'}, \quad (15)$$

$$tg\delta_k = \frac{k''}{k'} \quad (16)$$

Evaluating obtained results, we have arrived at the assumption that adding metal filler to auxetic matrix leads to decrease of energy dissipation in ultrasonic wave transmission for longitudinal and transverse deformations. Moreover, energy value depends on fillers material. Tangent of an angle $tg\delta_k$ is negative. In TPU-systems energy mechanical losses for absolute value in bulk deformation increase if to be compared with parent polymer.

TPU-system model, where metal filler content is critical, is presented as stated in paper [32]. As reported by the model metal filled TPU-system is a cubic macrolattice (in 3D modeling) with bulky sphere-shaped feller's particles in its nodes. Critical feller content in polymer matrix leads to its structural changes, i.e. polymer matrix transfer to interfacial state, where filled polymer properties differ from pure polymer. In this case, filled polymer is considered as two-component polymer: interfacial layer – nanofiller. In this context particles filler system regiments and its nodes movements immersed into interfacial layer, become dependent on their neighbor state. Related structurally consistent system is regarded as macrolattice with period:

$$l_{\max} = D_F \cdot \left(\frac{\rho/\rho_p + \varphi_{cr}}{1{,}91\varphi_{cr}} \right)^{1/3}, \quad (17)$$

double interfacial layer size equals to:

$$l_{IL} = D_F \cdot \left(\left(\frac{\rho/\rho_p + \varphi_{cr}}{1{,}91\varphi_{cr}} \right)^{1/3} - 1 \right), \quad (18)$$

where D_F – filler's particles diameter, ρ, ρ_p – filler and polymer density, φ_{cr} – critical filler contents.

$l_{max.}$ and l_{IL} values are presented in Fig. 2.

So far as $l_{max.}$ and l_{IL} values depend on filler's particles size, it indicates fractal structure formation of filled polymer system. Interfacial layer due to its structural consistence is nonuniform that is stipulated by force action on active centers macromolecular structural elements on filler's surface. Based on the model we have evaluated macrolattice deformation processes at ultrasonic wave transmission. Taking into account general auxetic deformation model [19], TPU-systems are regarded as rectangles subsystem set that rotates. Comparing TPU-composites dynamic Poisson's ratio with general model values enable to distinguish macrolattice parameters. So in TPU+W systems for

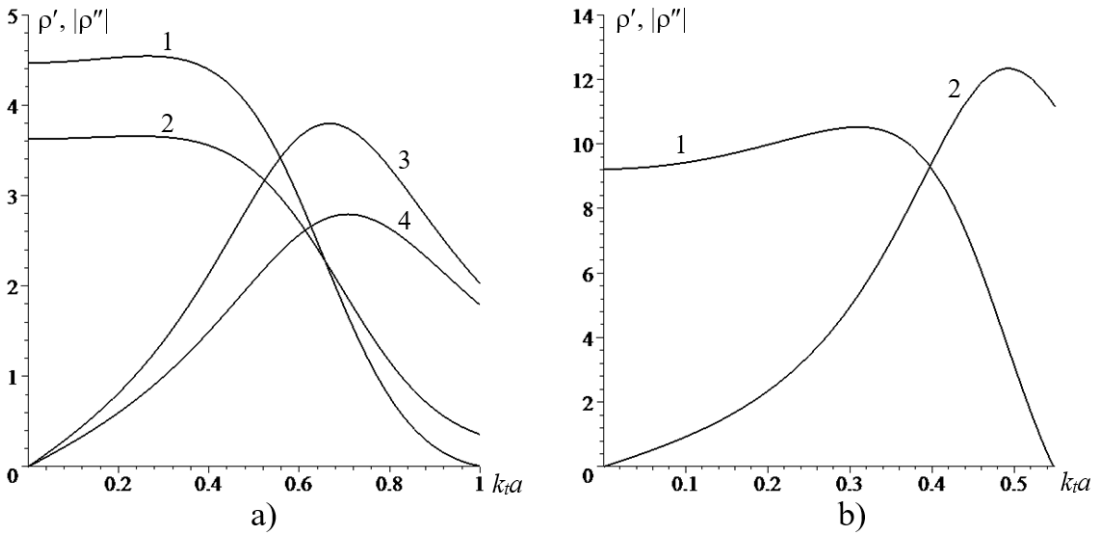

Fig. 3. Frequency characteristics of real (ρ′) a) (1, 2); b) (1) and imaginary (|ρ″|) a) (3, 4); b) (2) parts of complex density for TPU+Mo a) (1, 3); TPU+Fe a) (2, 4); TPU+W b) (1, 2).

a = 2, b = 1 values corresponding parameters are c = 2, d = 1 at slight rotation angles ($0° \le \theta \le 3°$) due to deformation process. In TPU + Fe, TPU + Mo systems we have values accordingly a = 2, b = 1, c = 1 ($0° \le \theta \le 5°$), d = 2; a = 2, b = 1, c = 3 and d = 4 ($0° \le \theta \le 7°$). It proves that macrolattice is rather trussed structure that can be modified by ultrasonic transmission having narrow rotating angle.

Simulating macrolattice deformation system of metal filler in polymer matrix [33], we change rectangles into squares and move from 3D to 2D model. As we look at the square group $x_0 = y_0 = l_{max}$ that undertakes deformation at ultrasonic waves transmission. For TPU + W systems macrolattice node shift is θ = 14°, and for TPU + Fe, TPU + Mo systems it is 17° and 18°.

So very elastic properties of auxetic environment with rather bulky inclusions can stipulate possibilities of resonance effects on structure deformation level. Suchlike systems can be regarded as complex density environments [34], where solid bulky inclusions of different shapes and sizes play role of absorbing elements and polymer is seen as matrix.

Let us consider auxetic environment, where ν < 0 and there are bulky sphere-shape inclusions, intending r = a inclusions radii $l_m = s$ distances between them are small, if to compare with longitudinal wavelength (λ_l) ($k_l a << 1, k_l s << 1$), and are commensurable with transverse wavelength (λ_t) ($k_t a \le 1, k_t s \le 1$), where k_l, k_t are longitudinal and transverse wave data. In this context, the environment can be considered as macrouniform compared to longitudinal wave, regarding resonance effects at inclusions fluctuation, as a separate structural subsystem.

Effective complex environmental density with sphere-shape inclusions is determined by the following ratio [34]:

$$\frac{\bar{\rho}}{\rho_1} = \rho' + i\rho'' = 1 + \frac{\varphi\left(\frac{\rho_2}{\rho_1} - 1\right)}{1 - \frac{(k_t a)^2}{(k_t a)_p^2} + i\left(\left(\frac{k_t a}{(k_t a)_p}\right)^2 \eta' + k_t a\right)}, \quad (19)$$

where ρ_1 – auxetic density, ρ_2 – inclusions density, φ – inclusions bulk concentration, $(k_t a)_p = \Psi (k_t a)_0$, $\eta' = \Psi tg\delta_\mu$, $tg\delta_\mu = \frac{\mu''}{\mu'}$ – shear losses, μ′, μ″ – real and imaginary parts of shear modulus, $\Psi = 1 + \frac{tg\delta_\mu}{2}(k_t a)_0$, $(k_t a)_0 = \sqrt{\frac{9\rho_1}{2\rho_2 + \rho_1}}$ – nondimensional resonance frequency discarding shear losses.

Calculation analysis (Fig. 3) shows that for composite polymer systems, based on auxetic environments, at small $k_t a$ values real part of complex density ρ′ approaches to its static value and is determined by $1 + \varphi(\rho_2/\rho_1 - 1)$ value, where relation ρ_2/ρ_1 in TPU-systems equals 8.2; 7.1; 16.8 for Mo, Fe, W. Increase in value $k_t a$ leads to not large ρ′ value growth and then sharp fall to less than unity values. It is caused by inertial to elastic reaction transmission.

Theoretical calculations of complex density imaginary parts data proved that ρ″ value is negative for every composite material in every $k_t a$ range of values unlike polymer materials with rubbery matrix, where ρ″ value is positive.

Functional dependence of |ρ″| value on $k_t a$ value is

of typical resonance nature with some $k_t a$ value maximum that correlates in different composites TPU + W, TPU + Mo and TPU + Fe: 0.51, 0.67 and 0.71.

Resonance point condition is $\rho' = 1$ and effective losses values are $\theta = \rho'/|\rho''|$ that equal accordingly to different composites TPU + W, TPU + Fe and TPU + Mo: 0.09, 0.39, 0.29 and $k_t a$ values are 0.55, 0.83, 0.77.

In critically filled polymer systems, spatial ordering occurs and filler's particle movement depends on neighbors interchange. λ_t data evaluation based on theoretical $k_t a$ resonance values and transverse transmission experimental values in metal filled TPU-systems with auxetic matrix proves that s and λ_t values differ by an order of magnitude. Apparently, in this case, one should change to range of values from $k_t s \le 1$ to $k_t s << 1$, but it requires further theoretical study.

Conclusions

Regarding ultrasonic waves decay ratio, speed results measurement we are able to calculate real and imaginary parts of Young's modulus and tangent of mechanical loss angle at longitudinal, transverse and bulk deformation. Research analysis of viscoelastic properties of filled polyurethane auxetics proves that they differ from respective traditional heterogeneous polymer systems properties. In particular, investigated systems are characterized by negative value of imaginary parts of complex bulk deformation modulus and respective tangent of mechanical loss angle value. Investigated viscoelastic modulus data regarding various theoretical approaches, show that they can be considered in non-linear distortion framework of polyurethane auxetic structure formation and ultrasonic waves transmission. Using filled polymer model, having critical filler amount, macrolattice period is defined and its dependence on size of metal filler parts is shown. That sort of structure formation can be regarded as percolation clusters that are fraught with fractal properties. Considering the model and auxetic deformation modulus for TPU-systems, structural and elastic parameters are defined.

Viscoelastic properties, their structure formation indicate such TPU-systems as effective complex density structures. If ultrasonic wave transmission occurs, effects take place in the materials in different subsystem structure formation.

Promising way of auxetic TPU-systems usage is to apply them as soundproof materials.

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В’язкопружні характеристики наповнених поліуретанових ауксетиків

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У роботі представлені експериментальні значення швидкостей поширення поздовжніх і поперечних ультразвукових хвиль та коефіцієнтів їх поглинання, отриманих за допомогою імпульсного імерсійного методу у зразках металонаповнених полімерних ауксетиків з поліуретановою матрицею. На основі отриманих результатів визначені коефіцієнт Пуассона, дійсні та уявні частини комплексних динамічних модулів пружності (модуля Юнга, модуля зсуву, модуля об’ємної деформації) і тангенс кута механічних втрат для поздовжніх, поперечних та об’ємних деформацій. Проаналізовано в’язкопружні властивості наповнених поліуретанових ауксетиків на основі різних теоретичних підходів. Для пояснення від’ємних значень коефіцієнта Пуассона для таких систем використана модель наповненого полімеру з критичним вмістом наповнювача та моделі деформацій ауксетиків. Визначено структурні параметри цих моделей для наповнених поліуретанових ауксетиків. Моделювання систем з масивними вузлами, що здатні поглинати та розсіювати ультразвукові хвилі, дозволило розглядати їх як матеріали з комплексною густиною. Показано, що при певних співвідношеннях параметрів хвилі і структурно-механічних властивостей середовища проявляються резонансні ефекти при коливаннях частинок наповнювача як включень в цілому.

Ключові слова: полімерний ауксетик, поздовжні та поперечні ультразвукові хвилі, коефіцієнт Пуассона, в’язкопружні модулі деформації, тангенс кута механічних втрат, комплексна густина середовища, явище резонансу.