FACTA UNIVERSITATIS
Series: **Mechanical Engineering**
https://doi.org/10.22190/FUME231018001S

Original scientific paper

MECHANICAL RESPONSE OF LAYERED STRUCTURES WITH INTERNAL LAYERS FROM METAMATERIALS EXPOSED TO DYNAMIC LOADINGS

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Abstract. *The article presents the results of the analysis of mechanical behavior of mechanical layered structures with metamaterial interlayers under dynamic loading. These structures can be used in lightweight structures for damping dynamic loads in transport and aerospace engineering. Structural elements with layers of the mechanical metamaterials have a low specific mass density and high specific strength characteristics. These multilayer structures have a high specific ability to absorb and dissipate the energy of external dynamic loads too. The results of numerical simulation of the response of multilayer structures to dynamic impacts obtained in this work indicate high specific energy absorption and dissipative properties, which make it possible to weaken the pulse amplitude after passing through the layered system and attenuate of cyclic impacts amplitudes. The results obtained indicate the possibility of creating effective mechanical damping structures of the type under discussion.*

Key words: *Layered structures, Metamaterial's interlayers, Auxetic metamaterials, Pentamode metamaterials, Mechanical response, Dynamic loading*

1. INTRODUCTION

The nonlinear dynamics of constructions containing elements made of metamaterials remains an urgent problem requiring research. The mechanical behavior of such structures under dynamic loading is determined by a combination of nonlinear effects caused by geometric nonlinearities due to large deformation, physical nonlinearities in the constitutive relationships of the component materials, and nonlinearities caused by possible mechanical instabilities of the deformable structural elements. Development of construction elements for damping vibration and pulse impacts on the aerospace technics is one of important modern problem [1]. Energy-absorbing metamaterials now used in

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engineering applications demanding the mitigation of mechanical pulse impact and attenuation of vibration amplitudes [2, 3, 4, 5]. Metamaterials and sandwich structures had been studied as dynamic absorbers for vibration reduction in the last decades due to the advances in new manufacturing technologies. Yang et al. [6] proposed a structure composed of tuned dynamic absorbers for vibration reduction without the use of viscous vibration damping materials in the broadband frequency range

Chen et al. [7] analyzed the influence of damping on the wave propagation of the elastic metamaterial. Li et al. [8] proposed a novel meta-lattice sandwich structure, and analyzed the speed and stresses in the lower face-sheet under impact and blast load through numerical simulation. Metamaterials currently are of interest for a wide variety of applications including damping systems. Xue et al. [9] indicated that welding is a unique construction technique for auxetic metamaterials. Therefore the perspective investigations of the metamaterials manufacturing by welding are important for reducing of the metamaterials production costs. In this regard, the layered structures and metamaterials made of Ti-5Al-2.5 Sn titanium alloy, which has good weldability and high ductility in a wide range of strain rates were studied in this research. Guo et al. [10] showed that mesoscopic deformation of the auxetic structure of a metamaterial goes through three typical stages: convergence, flattening and collapse, ending with the compaction stage. The geometry of the frame structure also has a significant influence on the auxetic characteristics and the resulting stresses [11]. Therefore, the adequate describing of a large plastic strain, damage and fracture of material in the elements of layered structures is important for prediction obtaining of the mechanical behavior of these structures under dynamic loads. A number of modifications of models and methods for were proposed in [12, 13, 14] for describing of mechanical behavior alloys patterns under large deformations. To describe the mechanical behavior of materials in 3D printed structures, hybrid machine learning technology can be used [15].

The purpose of this work is to estimate the absorbed and dissipative energy of layered structures with an interlayer of three types of metamaterials subjected to dynamic loading. The model of inelastic deformation and the criterion of plastic fracture of Ti-5l-2.5 Sn were tested to describe the deformation of three-layer structures with a metamaterial interlayer in a wide range of strain rates equivalent to plastic deformation and stress triaxiality. Estimates of energy absorption and dissipation of three-layer titanium structures with metamaterial interlayers under pulse and high-frequency harmonic loads have been obtained.

2. Model and Computational Details

2.1 Model of multilayered structures with metamaterials elements

The mechanical behavior of a three-layer structure under dynamic loading was studied by numerical simulation of pulse action on a three-layer structure with an internal layer of metamaterial. The loading diagram of the three-layer structure is shown in Fig. 1. The outer layers of structural materials in three-layer structures serve to distribute the effective load on the system and form a distributed load on the support.

The mechanical responses of three-layer structures made of alpha titanium alloys with an intermediate layer of a pentamode metamaterial and model auxetic metamaterials, the dissipative properties of which were studied in [4, 16], are considered.

Three-layer structures can be manufactured using selective laser melting technology or frame elements welding [9, 18]. Three types of interlayers are considered: pentamode metamaterials and two type auxetic metamaterials, which have significant differences in mechanical properties, including elastic properties. The metamaterials under consideration at the macroscopic level can be considered as isotropic media, for which, at small deformations, the elastic moduli are related by the relation:

$$B/G=(\boldsymbol{\nu}+1)/[3(0.5-\boldsymbol{\nu})] \tag{1}$$

where B is the bulk modulus, G is the shear modulus, $\boldsymbol{\nu}$ is the Poisson's ratio.

For auxetic metamaterials, the Poisson's ratio is $\boldsymbol{\nu}\leq 0$, therefore three-layer systems, with a middle layer of auxetic metamaterials, for which $\boldsymbol{\nu}\to -1$, $B/G\to 0$, as a result of which the velocities of bulk elastic waves $C_b = (B/\boldsymbol{\rho})^{1/2}$ are close to zero. Therefore, auxetic metamaterials have the ability to be an insulator of external vibration or impulse influences. For pentamode metamaterials, Poisson's ratio ($\boldsymbol{\nu}\to 0.5$), $G\to 0$, the value of the bulk modulus B depends on the geometric dimensions of the frame elements of the pentamode material.

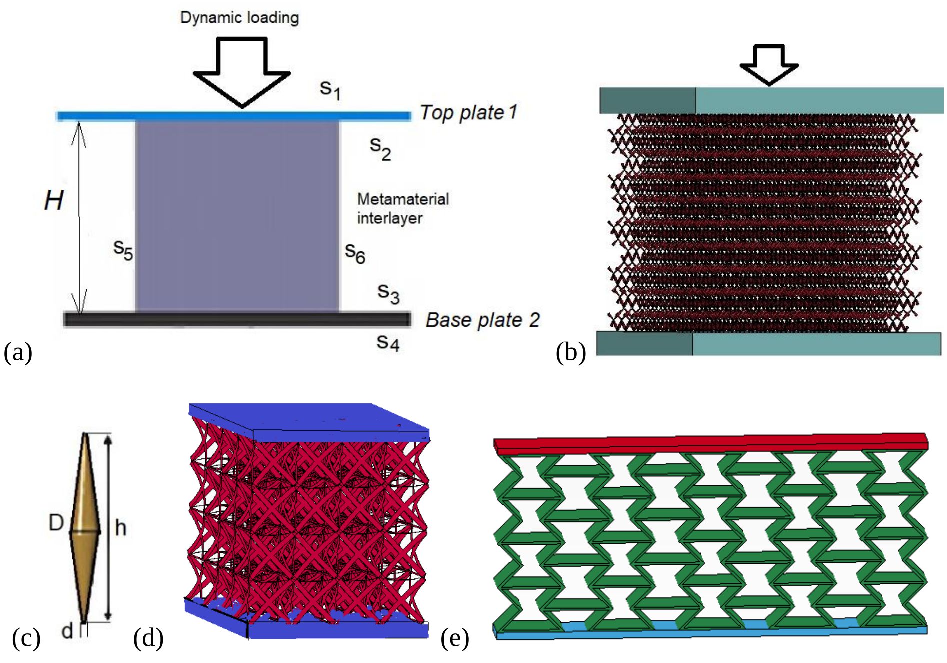

Fig. 1 Loading scheme of three layer structure (a), three-layer structure with an interlayer of pentamode metamaterial (b), geometry parameters of pentamode frame structural elements (c), structure with an interlayer of auxetic metamaterial (d), and with 3D re-entrant auxetic metamaterial (e)

For a pentamode material with a face-centered cubic frame lattice with the parameter *a*, and the diameter *d* in the touching region of frame elements the bulk modulus is determined as $B \sim d/a$, and the shear modulus is $G \sim (d/a)^3$ [11, 19]. Hedayati et al. [20] developed selective laser melting technology for manufactory of the pentamode metamaterials based on a titanium alloy. The results of [19] show that increasing the smaller diameter *d* and the ratio of larger to smaller diameter can increase the elastic modulus, while the Poisson's ratio remains almost independent of these variables and is constant around 0.5 in the considered range.

The possibility of additive manufacturing of pentamode materials with a normalized mass density $\boldsymbol{\rho}/\boldsymbol{\rho}_c$ from ~0.24 to ~4.24 ($\boldsymbol{\rho}_c$ is the mass density of the material of the frame elements) from the Ti-6Al-4V alloy powders is shown in [20, 21]. For a pentamode titanium alloy metamaterial, the relationship between effective compressive modulus and effective shear modulus has been shown to be influenced by the presence of stiffening plates, compared to existing theoretical predictions of the ratio of unconfined pentamode lattices [20].

The mechanical behavior of three-layer structure from Ti-5Al-2.5Sn (Grade 6) titanium alloys under dynamic loads was studied. The upper and base plates had dimensions in mm: 40×40×2.The thickness of metamaterial interlayer is 40 mm.

The elementary cell of the pentamode metamaterial interlayer had dimensions of 10 mm × 4.8 mm × 5 mm, and its frame element dimensions were equal $D = 0.4$ mm, $d = 0.11$ mm, $h = 1.6$ mm.

The cubic unit cell of the auxetic metamaterial under consideration (Fig. 1(d)) has a frame element width $D_w = 6$ mm, a thickness $D_a = 0.6$, and a distance between the upper and lower arcs of the frame elements a = 5.95 mm. The top and base plates had the same dimensions: 275×275×2 mm. The thickness of the metamaterial layer is 215 mm.

Three-layer structure with 3D re-entrant auxetic metamaterial interlayer (Fig. 1(e)) had thickness of upper and base plates 2 mm, and dimension 140 mm × 20 mm. The thickness of frame elements is equal to 1.0 mm. The thickness of the metamaterial interlayer is 87 mm.

2.2 Model of the mechanical behavior of a layered alpha titanium structure

Structural elements are deformed under dynamic loadings on the upper surface of three-layer structures. We investigated loading conditions under which plastic deformations occurred in structural elements, and frame elements of metamaterials changed their initial geometric shape. As a result of plastic deformations, micro damages and cracks can form in frame elements. The mechanical behavior of three-layer structures was described within the framework of the approach of mechanics of damaged elastic-viscoplastic media [12]. The constitutive equation of titanium alloy in frame element of metamaterials and plates was used in form:

$$\boldsymbol{\sigma}_{ij} = -p^{(m)}\,\boldsymbol{\varphi}_1(f)\boldsymbol{\delta}_{ij} + S_{ij} \tag{2}$$

where $\boldsymbol{\sigma}_{ij}$ is components of effective stress in damaged medium, $p^{(m)}$ is the pressure in condensed phase of frame elements, S_{ij} is deviator of effective stress tensor of damaged medium in material particles of frame elements, $\boldsymbol{\varphi}_1(f) = 1 - \ln(1 - f)$ is functions linking the effective pressure and its value in condensed phase of medium, superscript (*m*) denotes pressure in condensed phase of damaged material, *f* is the damage parameter.

In this study, using numerical modeling, we analyzed the mechanical response of three-layer systems with an interlayer of metamaterials created from alpha titanium alloy Ti-5Al-2.5Sn with good weldability and resistance to high strain rate plastic deformation under complex stress conditions [12]. A physical and mechanical model for describing alpha titanium alloys at high-strain rates is discussed in [22].

The initial temperature T_0 in the material of metamaterial unit cell was assumed equal to 295 K. The temperature increase at high strain rates was calculated in the adiabatic approximation, as proposed in [22].

The flow stress of alpha titanium alloys was described using constitutive equation:

$$\boldsymbol{\sigma}_s^{(m)} = \boldsymbol{\sigma}_{s0}\exp\{C_1\sqrt{(1-T/T_m)}\} + C_2\sqrt{1-\exp\{-k_0\boldsymbol{\varepsilon}_{eq}^p\}}\exp\{-C_3 T\}\exp\{C_4 T\ln(s_{eq}/s_{eq0})\} \quad (3)$$

where $s_{eq} = [(2/3)\,\dot{\boldsymbol{\varepsilon}}_{ij}\dot{\boldsymbol{\varepsilon}}_{ij}]^{1/2}$, $s_{eq0} = \gamma_1\exp(-T/\gamma_2)+\gamma_3$, $\dot{\boldsymbol{\varepsilon}}_{ij}$ is the components of strain rate tensor, $\boldsymbol{\varepsilon}_{eq}^p = \int_0^t \dot{\boldsymbol{\varepsilon}}_{eq}^p dt$ is the plastic strain intensity, γ_1=2115 s^{-1}, γ_2 =38.27 K^{-1}, γ_3 = 9.824 10^{-5} s^{-1}, T is the temperature, T_0 is the room temperature, and T_m is the melting temperature.

The following values of the model coefficients of Ti-5Al-2.5Sn were used in the calculations: $\boldsymbol{\sigma}_{s0}$ = 0.2 GPa, C_1 =385, C_2 =0.56 GPa, C_3= 0.0016 K^{-1}, C_4=0.00009 K^{-1}, k_0=85, T_m =1875 K [12, 22]. The grid convergence of the calculation results within a few percent was provided by the choice of the discretization step of the grid model.

2.3 Damage model

The Gurson - Tvergaard damage model was used for the yield stress determination in metamaterial elements [23]:

$$(\boldsymbol{\sigma}_{eq}{}^2/(\boldsymbol{\sigma}_S^{(m)})^2) + 2q_1 f^*\cosh(-q_2\, p^{(m)}/2\boldsymbol{\sigma}_S^{(m)}) - 1 - q_3(f^*)^2 = 0 \quad (4)$$

where $\boldsymbol{\sigma}_S^{(m)}$ is the yield stress of condensed phase, $p^{(m)} = -\boldsymbol{\sigma}_{kk}^{(m)}/3$ is the pressure in condensed phase, $\boldsymbol{\sigma}_{eq} = [(3/2)\boldsymbol{\sigma}_{ij}\,\boldsymbol{\sigma}_{ij} - 0.5\,\boldsymbol{\sigma}^2_{kk}]^{1/2}$, $\boldsymbol{\sigma}_{ij}$ is the effective stress tensor components, q_1 = 1.0, q_2 = 1.3, q_3 = 1.0, f^* is a damage parameter.

$$f^* = \{f H(f_c - f) + [f_c + ((1/q_1) - f_c)(f - f_c)/(f_F - f_c)]H(f - f_c)H(f_F - f_c)\} \quad (5)$$

where $f_F = [q_1+(q_1^2 - q_3)^{1/2}]/q_3$, $H(.)$ is the Heaviside function, f_c is the material constant.

The evolution of damage (growth and nucleation of discontinuities) and fracture of the material of unit cell of pentamode metamaterials was described by the Needleman model [23].

$$\begin{aligned} \dot{f} &= \dot{f}_{nucl} + \dot{f}_{growth} \\ \dot{f}_{nucl} &= \boldsymbol{\varepsilon}_{eq}^p (f_N/s_N)\exp\{-0.5[(\boldsymbol{\varepsilon}_{eq}^p - \boldsymbol{\varepsilon}_N)/s_N]^2\} \\ \dot{f}_{growth} &= (1-f)\dot{\boldsymbol{\varepsilon}}_{kk}^p \end{aligned} \quad (6)$$

where ε_N and s_N are the average strains at which damage nucleated and the strain standard deviation, respectively. The generated damages parameter f depends on the value of the parameter f_N. The values of model coefficients for alpha titanium alloy determined in [12, 22] were used: f_N = 0.04, S_N = 0.1, f_F = 0.26, f_c = 0.117.

2.4 Initial and boundary conditions

Numerical modeling of the response of three-layer systems to dynamic loads was carried out for initial conditions corresponding to the absence of residual stresses in the material of the elements, a uniform temperature field T_0, and the absence of damage (f = 0). Options for loading three-layer systems are considered, the diagram of which is presented in Fig. 1(a) were given by relations:

$$u_1\big|_{S_1}=0,\ u_2\big|_{S_1}=0,\ u_3\big|_{S_1}=v_z(t),\ u_1\big|_{S_4}=0,\ u_2\big|_{S_4}=0, u_3\big|_{S_4}=0,\ \boldsymbol{\sigma}_{ij}\big|_{S_2\cup S_3\cup S_5\cup S_6}=0 \qquad (7)$$

where u_i are the components of the velocity vector of material particles, $v_z\,(t)$ is the velocity of material particles on the loading surface, surfaces $S_1 – S_6$ are shown in Fig.1(a), surfaces S_5 and S_6 include the surfaces of the metamaterial frame elements.

The pulse amplitude $v_z^{(amp)}$ = 100 m/s was specified for pulse loading. During cyclic loading, the speed on the loading surface was specified by a harmonic function of time Loading frequencies f_{cycl} at which displacement of the top plate does not lead to complete compaction of the metamaterial layer are considered. The period of harmonic oscillation is equal to $T_c = 1/\,f_{cycl}$. These frequencies must satisfy the condition: $f_{cycl} > 0.25\ \ v_z^{(amp)}/[H – m/(\boldsymbol{\rho}_c F)]$, where H is the thickness of metamaterial interlayer, m is the mass of metamaterial interlayer, $\boldsymbol{\rho}_c$ is the mass density of material of metamaterial frame element, F if the square of metamaterial volume projection onto the base plate.

Loads with frequency 20 kHz and amplitudes from 100 m/s and below were considered.

Numerical simulation of the multilayer structures response to dynamic impacts was performed in the LS DYNA environment using the original UMAT module, which implements the constitutive equations describing the elastic-plastic behavior and damage of titanium alloys in a wide range of strain rates, temperatures, taking into account the influence of complex stress states.

3. RESULTS OF NUMERICAL SIMULATION AND DISCUSSION

The simulation results showed differences in the patterns of deformation development in layers of pentamode and auxetic metamaterials under dynamic loading. The mechanical response of the considered three-layer systems to dynamic influences is determined by the thickness of the metamaterial layer and the patterns of its deformation.

In the case of dynamic compression of three-layer systems, the deformation of the metamaterial layer depends on the initial effective mass density.

Fig. 2(a) shows the changes in average pressures on the lower surface of the top plate versus time (curve 1) and the lower plate (curve 2) for a three-layer system with an intermediate layer of pentamode metamaterial. Loading was carried out by a load pulse with amplitude of 100 m/s. Pressure oscillations (curve 1) are caused by changes in the compression resistance of the pentamode material in the contact zones of the metamaterial frame elements with the loading plate. Pressure relaxation is associated with a decrease in the resistance of the metamaterial layer to deformation at high strain rates as a result of collapse of the frame structure layer and partial fracture. Deformation, fracture and intensive compaction of the pentamode metamaterial frame structure in the interlayer is completed at time A ($t_A = t_0 + \Delta t \approx t_0 + H/v_z(t)$).

The damping capabilities of the three-layer system after time moment A will be exhausted. The simulation results shown in Fig. 2 (d), illustrate the scattering of fragments of the fractured frame structure of the pentamode metamaterial (zone B). Fig. 2(b) shows changes in time of the supplied energy (1), kinetic energy (2) and internal energy (3) of considered three-layer structure under the influence of a shock pulse.

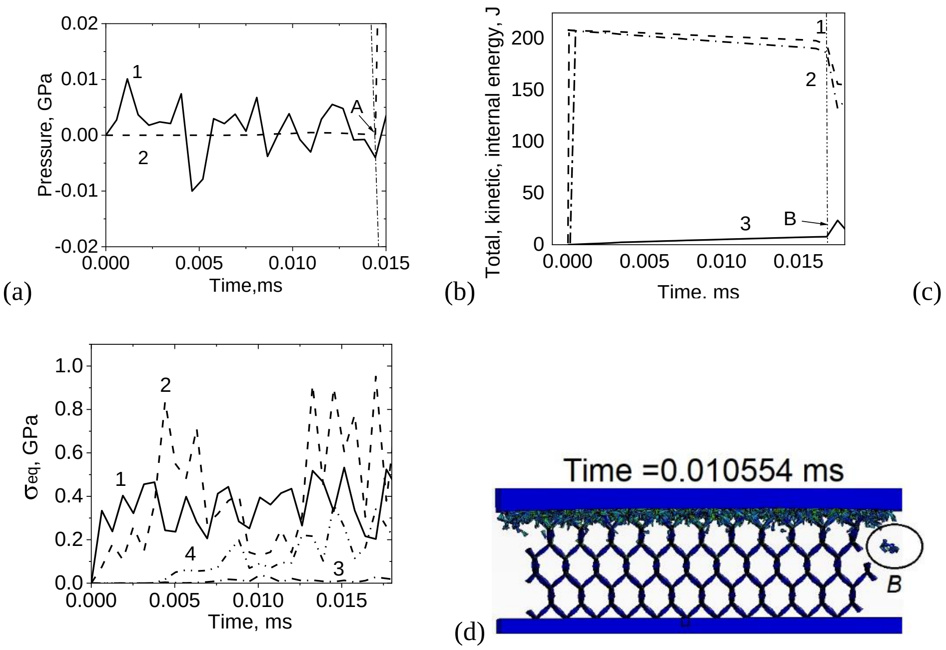

Fig. 2 Mechanical behavior of three layered titanium structure with pentamode metamaterial interlayer: pressure averaging on surface at upper plate curve 1) and at low plate surface (curve 2) versus time for pentamode interlayer (a), total, kinetic, and internal energy of layered titanium structure versus time (curves 1,2,3) (b), Mises equivalent stress in central points and connection zone of frame pentamode elements near top plate surface (curves 1,2) and near base plate surface (curves 3,4) (c), deformation and fracture of pentamode metamaterial interlayer in three layer structure under dynamic compression in normal direction to surface of the top plate (d)

The results of numerical modeling indicate significant damping properties of a layered structure with a pentamode metamaterial interlayer.

The damping properties of such three-layer systems are exhausted at time B, shown in Fig. 2(b) when the pentamode metamaterial layer is crushed, destroyed, and compacted. Fig. 2 (c) shows the time changes in equivalent stresses in the zone with the maximum diameter of pentamode metamaterial frame element (curves (1), (3)) and in the joint zone of the frame elements (curves (2), (4)). Curves (1) and (2) correspond to the frame element connecting with the top plate, and curves (3) and (4) to element in contact with the base plate. Oscillations of equivalent stresses in frame elements during compaction of the metamaterial are caused by stress relaxation due to local plastic deformation, accumulation of damage and fracture. Note the plastic deformation and fracture of frame elements in connection zone occurs in the complex stress states, which confirms the importance to take into account stress triaxiality parameter $\boldsymbol{\eta} = -p^{(m)}/\,\boldsymbol{\sigma}_{eq}^{(m)}$ for simulation of the response of pentamode metamaterial to dynamic compression.

The results in Fig. 3 demonstrate the mechanical response of a three-layer system with an auxetic interlayer (see Fig. 1(d)) to impulse impacts with amplitude of 100 m/s. Fig. 3(a) shows the changes in pressure versus time on the lower surface of the upper plate (1) and the lower plate (2).

The considered auxetic metamaterial has greater compressive rigidity compared to the considered pentamode metamaterial, as a result of which three-layer systems demonstrate higher resistance to pulsed compression. At time moment A, the elastic wave passes through the frame of the auxetic metamaterial and reaches the surface of the base plate.

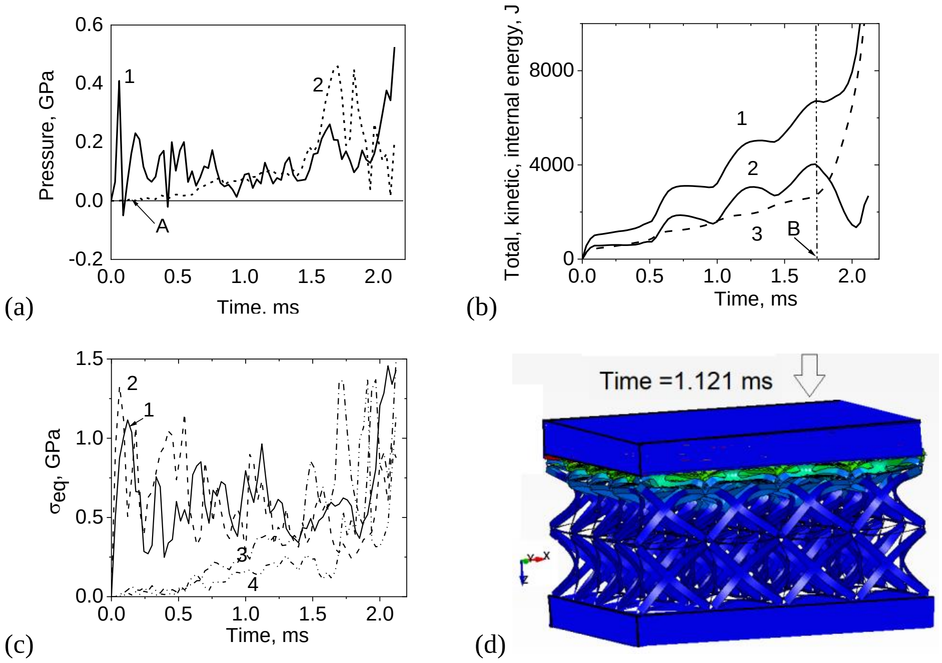

Fig. 3 Mechanical behavior of three layered titanium structure with metamaterial interlayer: pressure at upper plate surface (curve 1) and low plate surface (curve 2) versus time for pentamode interlayer (a), total, kinetic, and internal energy of layered titanium structure versus time (curves 1,2,3) (b), von Mises equivalent stress in central points and connection zone of pentamode frame elements near upper surface (curves 1, 2) and near lower plate surface (curves 3,4) (c), deformation and fracture of auxetic metamaterial interlayer in three layer structure under dynamic compression (d)

Pressure oscillations in the loading plate are caused by changes in the compressive resistance of the crushed metamaterial layers shown in Fig. 3(d). Plastic deformation of frame elements of an auxetic metamaterial is accompanied by dissipation of total mechanical energy. Fig. 3(b) shows the changes in mechanical (1), kinetic (2) and internal energy (3) supplied to the volume of a three-layer structure under pulsed loading. The drop of kinetic energy (curve 2) in the time moment B is associated with end of metamaterial compaction. The results indicate the ability of the considered structure to dissipate the supplied mechanical energy under pulsed influences. Dissipation of mechanical energy is associated mainly with inelastic deformations of the frame elements of the metamaterial. Changes of equivalent stresses in the central zone of frame elements (curves (1), (3)) and in zones of their connections (curves (2), (4)) near the loading plate and base plate are shown in Fig. 3(c). Oscillations of $\boldsymbol{\sigma}_{eq}$ are caused by the excitation of frame elements vibrations under the influence of a pulse load. The oscillations die out with increasing plastic deformation of the structural elements and compaction of the metamaterial layers. The compaction of the metamaterial layer occurs layer by layer, starting from the zone adjacent to the loaded plate, as shown in Fig. 3(d), and ends at time B (Fig. 3(b)).

Fig. 4 presents the results obtained by modeling pulse loading of three-layer systems with an interlayer of a more rigid auxetic metamaterial (Fig. 1(e)) [24]. In contrast to the three-layer system with a pentamode interlayer, in the system with an auxetic metamaterial made of alpha titanium alloy, no destruction of frame elements and joint zones was observed. An increase in the thickness of the metamaterial layer for both three-layer systems considered will lead to an increase in their dissipative properties and the duration of deformation until complete compaction.

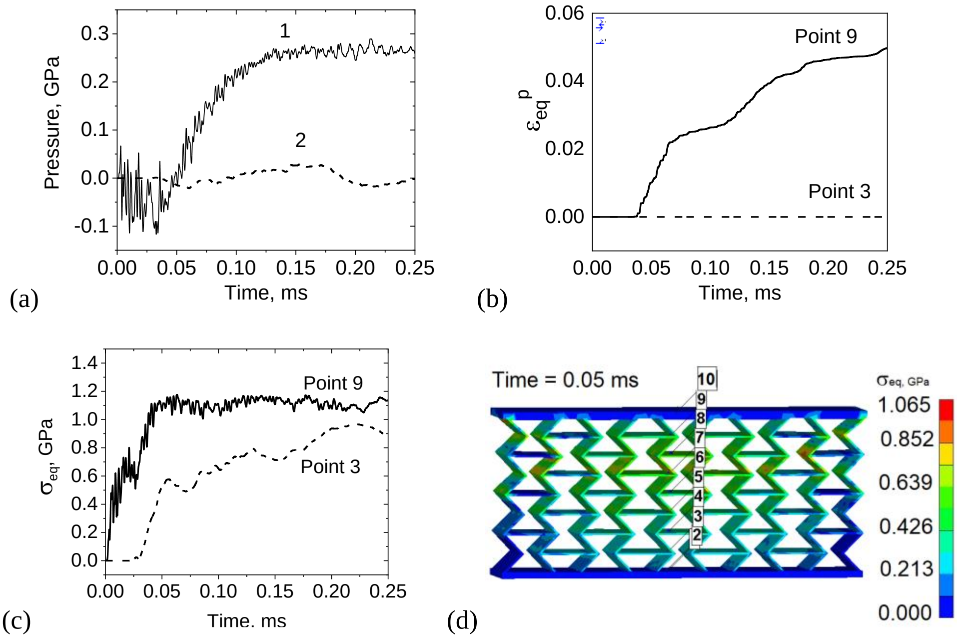

Fig. 4 Mechanical behavior of three layered titanium structure with auxetic re-entrant metamaterial (type 2) interlayer: pressure at the upper plate surface versus time (curve 1) and at low plate surfaces (curve 2) (a), equivalent plastic strain versus time in gage points 3, and 9 in frame elements of auxetic re-entrant metamaterial, respectively (b), Mises equivalent stress versus time in gage points 3, and 9 (c), Mises equivalent stress in three layered structure (d)

Pulsed loading of the top plate causes a stress wave to propagate along the metamaterial frame structure, which causes deflections of the frame elements oriented orthogonally to the direction of loading, as well as a decrease in the angles of the connected frame elements. Compaction of the frame elements leads to a significant decrease in pressure on the surface of the base plate (2) (Fig. 4(a)). A stiff auxetic re-entrant metamaterial under dynamic compression normal to the surface of the loading plate does not experience layer-by-layer collapse, as shown in Fig. 4(d).Vibrations of deformable frame elements during compression of the stiff auxetic metamaterial layer lead to oscillations of equivalent stresses, which are shown in Fig. 4 (c) at gage points 9 and 3, the positions of which are indicated in Fig. 4(d). These results suggested that three-layer systems with a stiff auxetic metamaterial interlayer could be used as high-amplitude harmonic dampers.

Fig. 5(a) shows the damping of the vibration amplitude of frame elements at gage points 10, 5 and 1.

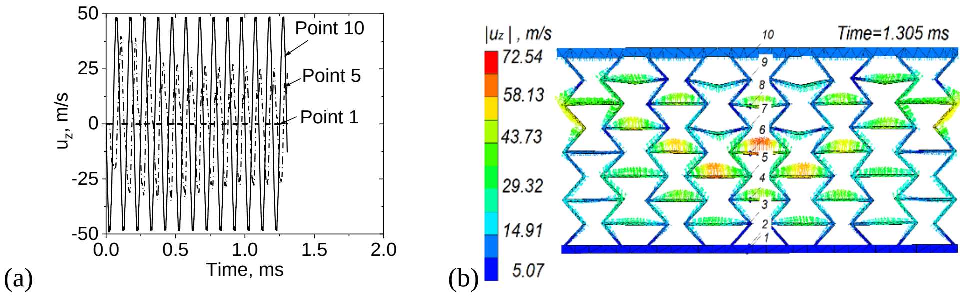

Fig. 5 Velocity versus time under harmonic loading of layered structure with stiff auxetic re-entrant metamaterial interlayer (a), distribution of local velocity vectors in frame elements (b)

The results of modal analysis for the considered three-layer system showed, that natural frequencies are 0.01066, 0.01294, 0.035, 190, 243, 264 Hz for the first 6 modes, respectively. The harmonic loading frequency was 20 kHz, and amplitude of the velocity oscillation 50 m/s.

Thus, the response of a three-layer system to harmonic influences was studied far from the induced band gap caused by resonance phenomena. Fig. 5(b) shows the amplitudes of the vibration speeds of the elements at the time instant of 1.305 ms. Results obtained indicate that three-layer systems with an auxetic intermediate layer can be insulators of high-amplitude vibration impacts.

The presence of horizontal frame elements significantly affects the relationship between the effective compression modulus and shear modulus estimates for unconfined pentamode lattices under quasi-static loadings. Therefore, the use of effective elastic moduli and theoretical constitutive relations obtained for unconfined pentamode lattices does not provide reliable predictions of the mechanical response of these layered systems under quasi-static and dynamic loading. The results of this research obtained for layered systems with an interlayer of auxetic metamaterials complement the results of [24-28] and confirm the position that topological differences in auxetic metamaterials affect the critical crushing characteristics and energy absorption capacity of systems. Note the nonlinear nature of the change in equivalent stresses and pressure in the elements of auxetic metamaterials in Fig. 3 and 4 are in qualitative agreement with the results of Zang et al. [26] and Wang et al. [28] for stresses and strains. The patterns of changes in energy absorption and energy dissipation under dynamic loading of layered systems with an interlayer of auxetic metamaterials are consistent with the results of [26, 27, 28]. The results of layered systems compaction simulation with an interlayer of auxetic materials under dynamic compression and the occurrence of oscillations of compressive stress are consistent with the results obtained by Novak et al [24] using a direct experimental researches of dynamic compression of metamaterial samples from titanium alloy, and results obtained by Zang et al. [28] for auxetic metamaterials from aluminum alloys.

4. Conclusions

Layered structures with pentamode or auxetic metamaterials interlayer are promising materials for applications in transportation and aerospace systems that require low weight, high strength, and high energy absorption.

The results obtained showed that in order to obtain realistic predictions of the mechanical response of these layered structures to dynamic loads, it is necessary to take into account a set of nonlinear geometric effects when describing large deformations of frame elements of metamaterials, nonlinearity of the elastic-viscoplastic constitutive equations and damage of the material at complex stress states.

It is shown that the considered layered systems made of alpha titanium alloy have high specific energy absorption and dissipative properties, which make it possible attenuating the amplitude of the stress pulse after passing through the layered system.

Increasing the rigidity of auxetic metamaterials by increasing the thickness of plate lattices in the interlayers of layered systems makes it possible to expand the range of amplitudes of cyclic loads that can be damped by such systems.

Acknowledgement: *The research was supported by the Russian Science Foundation* (*RSF*)*, project №23-29-00349.*

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