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Specific Damping Capacity of Layered Structures with a Layer of Dissipative Metamaterial under Quasi-Static and Dynamic Impacts

Vladimir A. Skripnyak*
Maxim O. Chirkov†
Vladimir V. Skripnyak‡
National Research Tomsk State University
Tomsk, Russian Federation

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Abstract. The article presents the results of the analysis of mechanical behavior of mechanical layered structures with auxetic metamaterials interlayers under dynamic and quasi static 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 modeling 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 vibration amplitudes. The results obtained indicate the possibility of creating effective mechanical damping structures.

Keywords: layered structures, mechanical response, dynamic loading, specific damping capacity, metamaterials interlayers, auxetic metamaterials.

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Introduction

Aerospace engineering designs with elements made from advanced metamaterials, developed over the last decade, have made it possible to achieve mass savings and effective damping of vibrations arising during operation [1, 2]. These damping systems with limited mass design for reducing vibrations have to possess the ability to damp vibrations over a wide range of frequencies and temperatures. An innovative approach to solving these problems is the development of layered structures with internal layers made of metamaterials [3]. The dynamic response of such structures to vibration leads to the appearance of a stopband corresponding to a wide range of frequencies with strong vibration attenuation. The studies on the energy absorption properties of lattice structures sharply increased trend year by year, as shown in [4, 5]. The dynamic behavior of auxetic metamaterials used in damping structures has been studied by a number of authors [6–9]. A design combining dynamic absorbers that do not use viscous vibration-damping materials has been proposed to reduce vibration in a wide frequency range [10]. This work

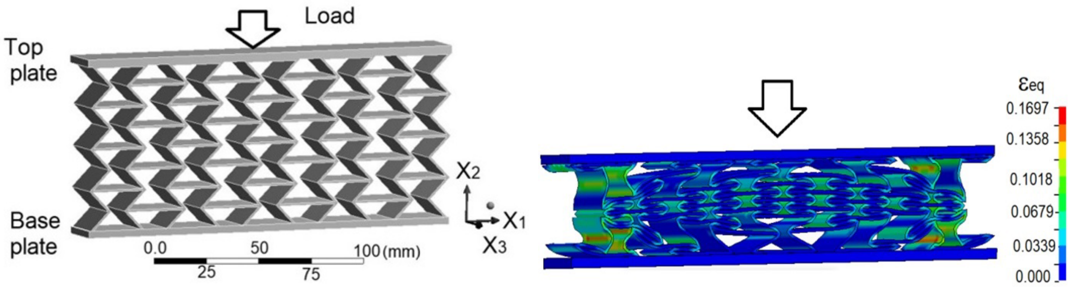
*skrp2006@yandex.ru https://orcid.org/0000-0001-7162-3983
† https://orcid.org/0000-0002-1801-5871
‡ https://orcid.org/0000-0003-2238-5856

is aimed to evaluate dissipative effect of layered structures with a layer of auxetic dissipative metamaterial subjected to dynamic loading. The mechanical behavior of layered structures with interlayer auxetic metamaterials from 1520 aluminum alloy was studied under pulse loadings and harmonic cyclic loadings by numerical simulation method. The Johnson–Cook model of inelastic deformation and ductile damage criterion was used to describe the ductility of the framework of metamaterials in a wide range of strain rates, temperature, and stress triaxiality. The specific energy dissipation of 3D layered structures under dynamic loadings was estimated using results of numerical simulation.

1. Model and computational details

1.1. Model of multilayered structures with metamaterials elements

The mechanical response of a three-layer structure to dynamic and quasi sttic loading was studied by numerical simulation. The model of three layer structure with an intermediate layer of auxetic metamaterial in initial state is shown in Fig. 1 (a). The deformed layered structure ufter dynamic impacts on the surface top plate is shown in Fig. 1 (b).



(a) (b)

Fig. 1. (a) Initial shape of three layer structure with an interlayer of auxetic metamaterial, (b) equivalent plastic strain in deformed layered structure as a result of pulse loading with an amplitude of 25 m/s for 2 ms

The top and base plates had the same thichness of 2 mm, the dimension of plates is 140 × 20 mm, and the total thickness of layered structure was $H=$ 87 mm. The thickness of frame metamaterial elements is 1.0 mm. In this work, we analyzed three-layer structure made of aluminum alloy 1520 (AMg2, an analogue of the AA5052 alloy). This alloy has good weldability and resistance plastic strain at high strain rates and is convenient for the manufacture of three-layer systems. Mass of three layer structure is 0.1524 kg. Mass of auhetic metamateria interlayer is equal 0.1224 kg. the average mass density of metamaterial interlayer is equal 522 kg/m^3. The loading was applyed to the upper surface of top plate.

1.2. Model of mechanical behavior of 1520 aluminum alloy

The mechanical response of the volume of a three-layer structure to dynamic influences was studied by numerical simulation using LS DYNA in WB ANSYS 19.2 [11]. The yield strength of a condensed material with an FCC lattice was described using the following constitutive relation [12]:

$$\sigma_s = \left[C_0 + C_1 \left(\varepsilon^p_{eq}\right)^n\right]\left[1 + C_2 \ln\left(\dot{\varepsilon}*\right)\right]\left[1 - \left(T*\right)^m\right] \quad (1)$$

where (C_0, C_1, C_2, n, m) are the constants of the material, $T^* = (T - 295K)/(T_{melt} - 295K)$ is the normalized temperature, T is the temperature on an absolute scale, ε^p_{eq} is the equivalent plastic strain, $\dot{\varepsilon}^* = \dot{\varepsilon}_{eq}/1\,s^{-1}$ is the normalized equivalent strain rate. The evolution of damage to the aluminum alloy under dynamic loading was determined using the Johnson–Cook model [12]. According to the model, the fracture region is associated with triaxial stress state and equivalent plastic deformation:

$$\varepsilon_f = [D_1 + D_2 \exp(D_3)\eta)\,][1 + D_4 \ln(\dot{\varepsilon}^*)][1 + D_5 T^*], \tag{2}$$

where ε_f is the equivalent plastic strain at fracture of the material, $D_1 \ldots D_5$ are the material constants, $\eta = -p/\sigma_{eq}$ is the stress triaxiality factor of stress state, p is the pressure, σ_{eq} is the Mises equivalent stress. The local fracture criterion is determined by relation [12]:

$$f_0 + \sum \left(\frac{\Delta\varepsilon_{eq}}{\varepsilon_f} \right) = 1, \tag{3}$$

where $\Delta\varepsilon_{eq}$ is the increment of equivalent plastic strain, f_0 is the damage of alloy in the initial state.

The authors conducted experimental studies of the mechanical behavior of this alloy in the range of strain rates from 0.001 to 1000 s^{-1} and calibrated the relationships of the Johnson-Cook model. The mechanical behavior of 1520 aluminum alloy can be described by JC model using the following values of coefficients: $C_0 = 90$ MPa, $C_1 = 335$ MPa, $n = 0.34$, $C_2 = 0.008$, $m = 2.01$, $T_{melt} = 923$ K, mass density at the temperature 295 K is equal to $\rho = 2.68 \cdot 10^3$ kg/m^3, Young's modulus $E = 70.3$ GPa, static tensile strength, 228 MPa; shear modulus $\mu = 25.9$ GPa, Poisson's ratio $\nu = 0.33$, melting temperature $T_{melt} = 923$ K, coefficient of linear thermal expansion $23.7 \cdot 10^{-6}$ K, thermal conductivity coefficient 138 W/m $\cdot$ K, the bulk modulus, $B = 69.92$ GPa, derivative of the bulk modulus with respect to pressure $B_1 = 4.8$, included in the Birch–Murnaghan equation of state [13], the specific heat capacity is equal to 0.880 kJ/kg $\cdot$ K.

The energy dissipation coefficient was used for characterizing dissipative properties of layered structures with metamaterial interlayer skeleton at high strain rates [8]:

$$\lambda(t) = \int_0^t \frac{\Delta W^S(t)}{W^S(t)} dt \tag{4}$$

where λ is the energy dissipation coefficient, $\Delta W^S(t) = W^S(t) - W^S_{int}(t)$ is the increment of specific dissipated energy, m is a mass of layered structure volume, W^S is the absorbed energy, W^S_{int} is the internal energy of layered structure volume. The specific absorbed energy W^S supplied to the model volume of layered structure under pulse loading was calculated by relation:

$$W^S(t) = \frac{1}{m_0} \int_0^t F(t) u(t) dt, \tag{5}$$

where $u(t)$ is the displacement of the upper surface of the layered structure, $F(t)$ is the calculated force on the upper surface of the top plate, m_0 is the initial mass of the volume of the layered structure. The value of the specific internal energy of the structure volume was calculated by the formula:

$$W^S_{int}(t) = \frac{1}{m_0} \int\limits_v \left(\int\limits_0^{\varepsilon^e_{ij}} \sigma_{ij}\, d\varepsilon^e_{ij} \right) dv, \tag{6}$$

where W_{int} is the internal energy of deformed volume of layered system, V is the volume, σ_{ij} is the stress tensor components, calculated in the material points within elements of layered system, $d\varepsilon^e_{ij}$ is increments of the elastic stain tensor components.

1.3. 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=0).

$$\begin{aligned} &u_1|_{S_1} = 0, \ u_2|_{S_1} = 0, \ u_3|_{S_1} = v_2(t), \\ &u_2|_{S_4} = 0, \ \sigma_{ij}|_{S_2 \cup S_3 \cup S_5 \cup S_6} = 0, \end{aligned} \tag{7}$$

where u_i are the components of the velocity vector of material particles, $v_2(t)$ is the velocity of material particles on the loading surface,

2. Results of numerical simulation and discussion

The absorbed and dissipative properties of the considered three-layer systems under pulse impacts depends significantly on the deformation and compaction of the auxetic metamaterial layer. In the process of deformation and compaction of the metamaterial interlayer up to specific effective mass density up to 0.95, the specific damping properties of the three-layer systems significantly decrease due to changes of the dissipative characteristics of the deformed and damaged metamaterial layer. The decrease in the increment λ in the time range AB showing in Fig. 2 (a) is caused by collapse of metamaterial interlayer. Fig. 2 (b) shows that the specific inter-

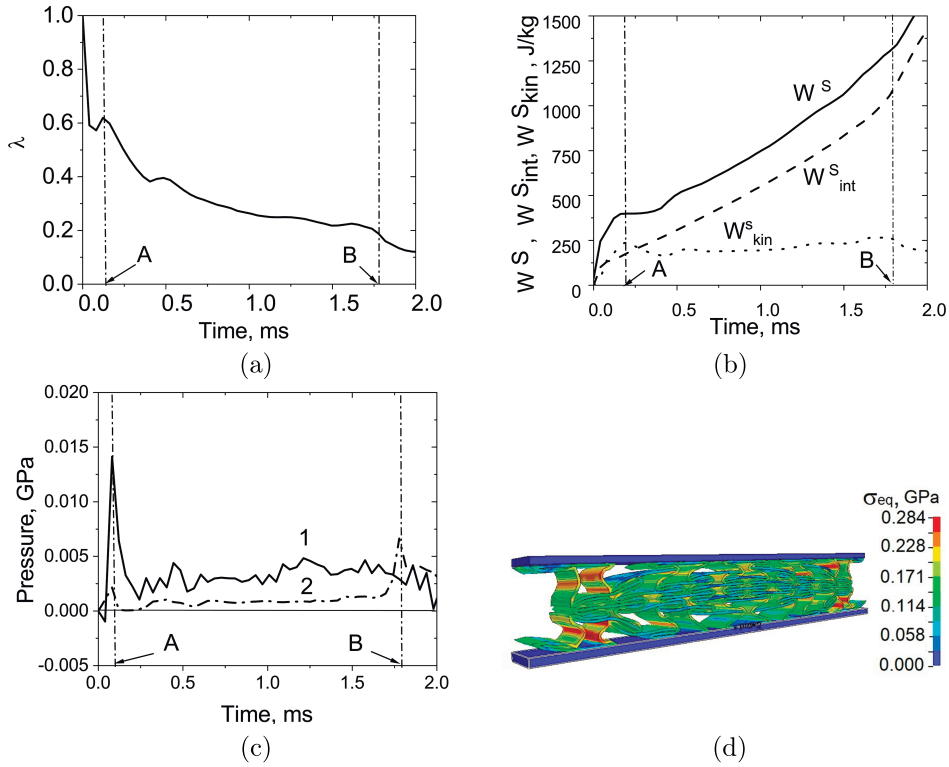


Fig. 2. (a) Increment of energy dissipation coefficient of three layered 1520 aluminum alloy structure with auxetic metamaterial under pulse loading with amplitude 25 m/s, (b) specific internal energy of deformed volume of layered system, specific absorbed energy, specific kinetic energy, (c) average pressure versus time on the surface of the top (1) and base (2) plates, (d) equivalent stress versus time in deformed layered structure as a result of pulse loading with an amplitude of 25 m/s for 2 ms

nal energy W^s_{int}, specific absorbed energy W^s, specific kinetic energy W^s_{kin} of deformed layered structure volume are increased with growth of time of loading. During the deformation of the metamaterial frame, oscillation of the average pressure at the surface of the top plate (curve 1) occurs, but on and base plates the average pressure (curve 2) remains at a low level until the metamaterial frame structure is compacted. The normal displacement of the loading plate under an impulse loading is determined by $w(t_B) = \int_0^{t_B} v_2(t)dt$. Compaction of the metamaterial frame structure in the interlayer is completed at time moment B $t_B = t_0 + \Delta t \approx t_0 + H/v_2\,(t)$, after which the damping capabilities of the three-layer system will exhausted. The compaction of auxetic metamaterial interlayer is accompanied by a decrease in the vibration amplitudes of the frame elements, resulting in a sharp decrease in the absorbed kinetic energy from the external dynamic load. As a result of deformation of the metamaterial structure during pulse loading of a three-layer structure, equivalent stresses (see Fig. 2 (d)) and equivalent plastic strains (Fig. 1 (b)) increase in the frame elements.

Conclusion

The studied layered systems based on aluminum alloy 1520 have the ability absorbing the energy of pulsed impacts and dissipative properties in a limited range of loading amplitudes, making it possible to weaken the amplitude of the stress pulse under it passing through the layered system. Adequate predictions of the mechanical response of layered structures of the considered class to quasi-static and dynamic loads can be obtained taking into account a complex of nonlinear effects when describing large deformations of metamaterial frame elements and the elastic–viscoplastic behavior and damage of auxetic metamaterial frame elements in complex stress states. Layered structures from light alloys with auxetic metamaterials interlayer are promising layered structures for applications in transportation and aerospace systems that require low weight, high energy absorption and high specific damping capacity.

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Удельная демпфирующая способность слоистых конструкций со слоем диссипативного метаматериала при квазистатических и динамических воздействиях

Владимир А. Скрипняк
Максим О. Чирков
Владимир В. Скрипняк
Национальный исследовательский Томский государственный университет
Томск, Российская Федерация

Аннотация. В статье представлены результаты анализа механического поведения механических слоистых конструкций с прослойками ауксетических метаматериалов при динамическом и квазистатическом нагружении. Данные конструкции могут быть использованы в облегченных конструкциях для гашения динамических нагрузок в транспортной и аэрокосмической технике. Элементы конструкций со слоями механических метаматериалов имеют низкую удельную массовую плотность и высокие удельные прочностные характеристики. Эти многослойные конструкции обладают высокой удельной способностью поглощать и рассеивать энергию внешних динамических нагрузок. Результаты численного моделирования реакции многослойных структур на динамические воздействия, полученные в данной работе, свидетельствуют о высоких удельных энергопоглощающих и диссипативных свойствах, позволяющих ослабить амплитуду импульса после прохождения слоистой системы и ослабить амплитуды колебаний. Полученные результаты указывают на возможность создания эффективных механически демпфирующих конструкций.

Ключевые слова: слоистые структуры, механическое реагирование, динамическое нагружение, удельная демпфирующая способность, прослойки метаматериалов, ауксетические метаматериалы.