ISSN 1392–1207. MECHANIKA. 2014 Volume 20(5): 466–470

Investigation of elasticity of magnetosensitive adaptive materials for laminated composite structures

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http://dx.doi.org/10.5755/j01.mech.20.5.7080

1. Introduction

Nowadays it is difficult to find a branch of modern engineering, which does not use structures of composite materials. Tendency to get the lowest material consumption of goods retaining the required strength and stiffness, as well as the possibility of varying material properties by changing the structure of reinforcement led to the use of composite beams, plates and shells of layered structure as constituting elements of thin engineering structures in various industries (in machine, tractor and shipbuilding, aviation and space technology, etc.) [1–4]. It is possible to improve the mechanical parameters of thin-walled elements of engineering structures by varying the rheological properties of viscoelastic layers in the construction of composite beams, plates and shells of layered "sandwich" structure using materials changing their viscoelastic properties under electric or magnetic fields influence [5, 6].

The most of works regarding controlled material-based layered structures dedicate to the vibration and damping characteristics in the pre-yield regime. Practically there are no significant investigations of characteristics of composite materials for laminated structures in the post-yield regime or in the creep mode. Yalcintas and Dai [6] analyzed the vibration control capabilities of adaptive structures made of electrorheological and magnetorheological materials, and compared their time responses and energy consumption rates. Sun et al. [7] used oscillatory rheometry techniques to obtain the dependence of the complex shear modulus of magnetorheological materials on the magnetic field intensity in the pre-yield regime. Yeh et al. [8] used the finite element and harmonic balance methods to calculate the instability regions of the sandwich beam with an electrorheological fluid core subjected to an axial dynamic force. Yeh and Chen [9] used the finite element method to investigate the effects of the core thickness ratio and electric field on the natural frequency and modal loss factor of the sandwich beam. Yeh and Shin [10] have derived the buckling load, the natural frequency, and the modal loss factor of a simply supported magnetorheological material-based adaptive symmetric three-layer beam; the dynamic instability and the dynamic response of the beam subjected to an axial harmonic load are determined.

2. Experimental

For the purpose of use in thin-walled constructions as layers of the adaptive composite materials changing their viscoelastic properties under magnetic field influence, we have developed compositions of materials which represent high-filled pastes containing as dispersed phase particles, sensitive to magnetic field influence, and the reinforcing particles forming thixotropic structural grid. As magnetosensitive dispersed phase highly dispersed (about 3 μm) particles of magnetosoft carbonyl iron are used, silica particles (bentonite clay, aerosil) serve as reinforcing (creating spatial thixotropic matrix) ones. As the disperse media synthetic or mineral oil was applied. Preliminary treatment of carbonyl iron particles with surfactants has allowed to prepare samples of magnetorheological two-component material (MRF), containing up to 85 wt. % of dispersed phase.

Rheological properties of MRF and their changes kinetics carried out using rheometer Physica MCR 301 by Anton Paar which employs the measuring cell of the plate – plate type with diameter 20 mm. Upper plate may turn with given angular velocity, or deflection angle, or applied shear stress τ. Measurements were carried out in the following modes: 1) linear growth of shear stress, when τ changes by the law $\tau = at$ (a is assigned constant rate of shear stress increasing), value of shear deformation ε is measured; this mode allows to define deformation curves and yield stress; 2) a creep mode: initially constant shear stress τ is applied, it is maintained some time, then $\tau = 0$ is established, dependence of strain ε on time t is fixed; 3) sinusoidal tangential oscillations of the top plate with constant frequency $f = 10$ Hz and amplitude of deformation ε_a in a range of values 0.0001–1 (deformation changes by the law $\varepsilon = \varepsilon_a \sin(2\pi ft)$; shear stress also change harmonically, but with advance in phase angle δ ($0<\delta<\pi/2$): $\tau = \tau_a \sin(2\pi ft + \delta)$; components of the complex shear modulus $G^* = G' + iG''$ are measured, where G' is the storage modulus (the elasticity modulus), proportionality coefficient between ε and constituent of τ in phase with deformation, G'' is the loss modulus, proportionality coefficient between ε and constituent of τ with advance in phase by $\pi/2$.

3. Results and discussion

In Fig. 1 the dependences of shear stress τ on deformation ε for magnetosensitive material on the basis of carbonyl iron particles (40 vol. %) and aerosil, received by a method of linear growth of shear stress are given. The investigation showed, that there is a considerable linear range in which shear stress and deformation are proportional in the deformation beginning, then prior to the start of a plastic flow the range of nonlinear change of shear stress is characteristic. Dependences of MRF yield stress, received in a mode of linear growth of shear stress, are shown in Fig. 2. The yield stress characterizes shear stress at which there is transition of MRF to viscoplastic condition. For giving of additional rigidity to constructions with adaptive materials it is necessary, that their deformations did not go outside of viscoelastic range.

For MRF on the basis of carbonyl iron particles (28 vol. %) and bentonite clay shear stresses, characterizing the beginning of fluid plastic flow, increase by three order (from 13 Pa to 31.4 kPa) in the magnetic field with induction 1 T, and for a material on the basis of carbonyl iron particles (40 vol. %) and aerosil – from 20 Pa to 29 kPa (Figs. 1, 2).

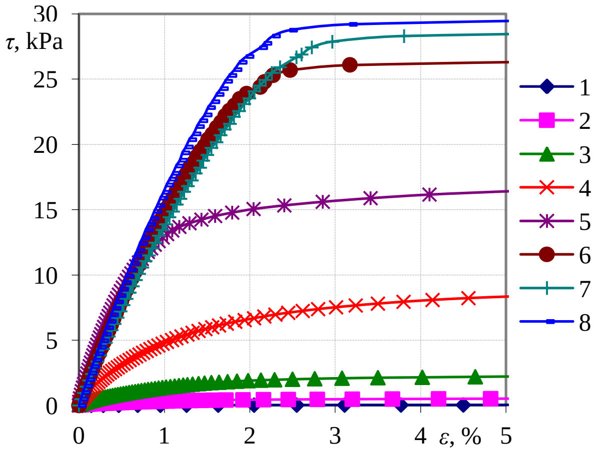


Fig. 1 Deformation curves of MRF on the basis of carbonyl iron particles and aerosil in the magnetic field: *1* – $B = 0$, *2* – $B = 50$ mT, *3* – 100 mT, *4* – 200 mT, *5* – 300 mT, *6* – 500 mT, *7* – 700 mT, *8* – 1000 mT

The kinetics of rheological properties changes of magnetosensitive two-component material on the basis of carbonyl iron particles and aerosil in creep mode is also investigated. In the initial moment of time the magnetic field of given intensity is turned on and shear stress is applied to the sample. Creep curves that represents deformation as a function of time was determined. After the time interval (500 s) the application of shear stress was stopped. Examples of creep curves of magnetosensitive two-component material at the constant applied loading and the constant magnetic field in a range of magnetic field induction up to 0.5 T and a range of shear stress 50 Pa – 2 kPa are shown in Figs. 3, 4.

Character of creep curves allows to assume, that they can be described by Burgers model which represents combination connected in series viscoelastic models of Kelvin–Voight and Maxwell (Fig. 5). In mode of creep dependence of deformation on time for medium described by Burgers model is expressed by the formula

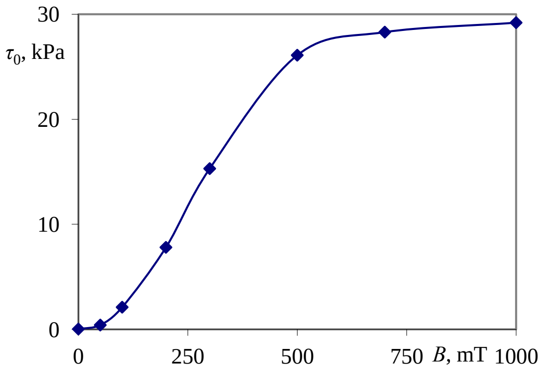
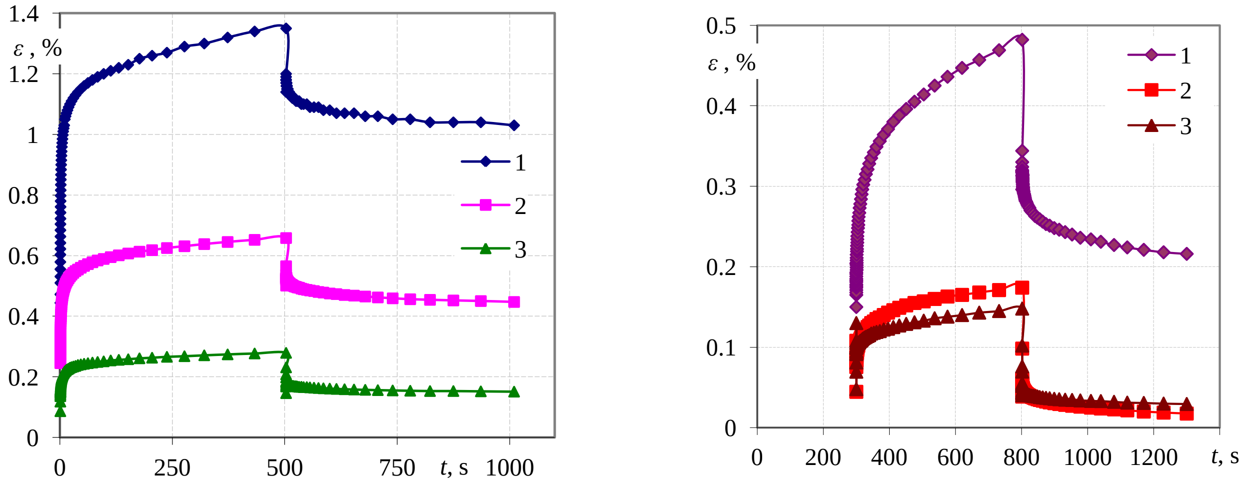


Fig. 2 Dependence of yield stress of MRF on the basis of carbonyl iron particles and aerosil on magnetic field induction



a b

Fig. 3 Dependences of deformation ε on time *t* (creep curves) of MRF on the basis of carbonyl iron particles and aerosil at shear stress $\tau = 2000$ Pa without exposition in the field (a) and with exposition in the field for 5 min (b): *1* – $B = 200$ mT, *2* – 300 mT, *3* – 500 mT

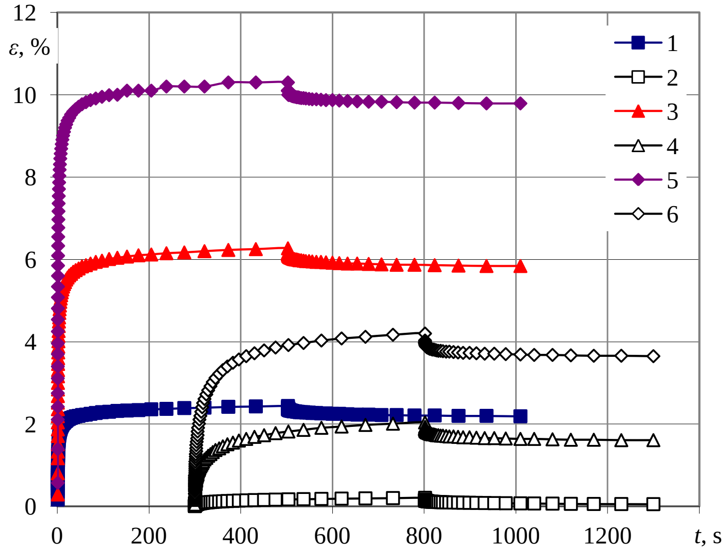


Fig. 4 Dependences of deformation ε on time t (creep curves) of MRF on the basis of carbonyl iron particles and aerosil at the magnetic field induction B=100 mT without exposition in the field (*1*, *3*, *5*) and with exposition in the field for 5 min (*2*, *4*, *6*): *1*, *2* – 400 Pa, *3*, *4* – 800 Pa, *5*, *6* – 1200 Pa

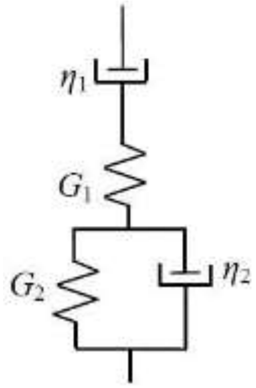


Fig. 5 Viscoelastic rheological Burgers model

$$\varepsilon(t) = \frac{\tau}{G_1} + \frac{\tau}{G_2}\left(1 - e^{-\frac{G_2 t}{\eta_2}}\right) + \frac{\tau}{\eta_1} t, \qquad (1)$$

where τ is applied shear stress, G_1, η_1 are elasticity modulus and viscosity coefficient of Maxwell element, G_2, η_2 are elasticity modulus and viscosity coefficient of Kelvin-Voight element.

At the initial moment of time at the shear stress application a deformation jump is observed corresponding to instant elastic deformation as a result of stretching of elastic Maxwell element $\varepsilon_1 = \tau/G_1$. Then eventually the retarded viscoelastic deformation concerned with Kelvin-Voight element develops which at times $t >> \eta_2/G_2$ reaches equilibrium value τ/G_2. At the third stage purely viscous deformation concerned with Maxwell element η_1 develops which starts to work after Kelvin-Voight element has reached an equilibrium condition. At this stage, the slope of deformation – time curve is constant and also is equal to shear rate τ/η_1.

In our case values of the retarded viscoelastic and viscous deformations are essential lower, than instant elastic deformation, the elastic properties prevail in high-filled systems. The beginning of a stage of viscous deformation occurs at times 70–80 s from the deformation beginning without dependence from values of applied shear stress and the magnetic field induction.

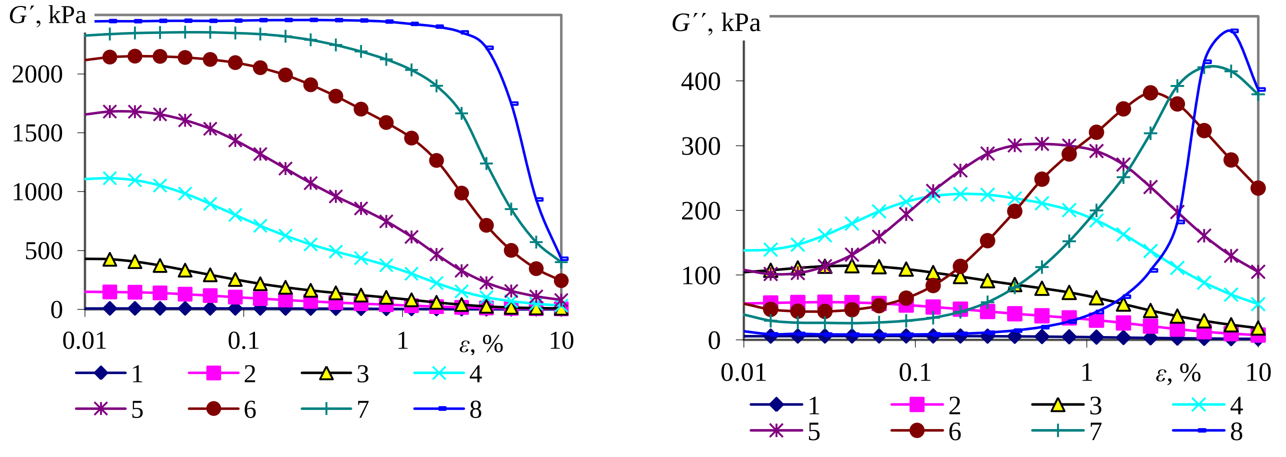
After eliminating of τ partial relaxation of deformation occurs, however the most part of deformation is irreversible, that testifies to destruction of spatial structure of disperse phase particles in the course of deformation and to weakening of elastic properties.

With growth of the magnetic field induction the part of reversible deformations increases, the field favours partial restoration of structure. So at $B < 200$ mT reversible deformations give less than 10 % of the contribution to the general value ε (Fig. 4). At the magnetic field induction 200 mT and more the part of reversible deformations increases up to 50% (Fig. 3, b), i.e. the elasticity modulus G_1 during of deformation decreases only 2 times.

In series of experiments prior to the beginning of deformation samples were exposed to the magnetic field for 5 minutes. The preliminary exposition in the magnetic field reduces creep deformation by several times. It testifies that process of structurization under the influence of a magnetic field takes some time. Without preliminary exposition structure of the sample is weaker. According to the character of creep curves we may conclude, that the exposition in the field increases the elasticity modulus, but values of the retarded viscoelastic and viscous deformations essentially do not change, as change rate of deformation is approximately identical in both cases.

Dependence of components of the complex shear modulus on deformation amplitude is shown in Fig. 6. Deformation at which transition of MRF into viscoplastic condition occurs (G' starts to decrease, and G'' has a maximum) monotonously increases with growth of the magnetic field induction (from 0.01% at $B = 0$ to 7% at $B = 100$ mT).

In Fig. 7 dependences of component of the complex shear modulus G^* at the shear deformation equal of 0.01% are given. The storage (elasticity) modulus increases considerably with the growth of intensity of an external field – in the beginning quasi-linear, then non-linear to range of weak nonlinearity and saturation (at $B > 300$ mT). The increase exceeds 3 order in the investigated range of the magnetic field induction. The loss modulus of magnetosensitive material has a maximum in range B 100 – 250 mT, then it decreases to values 10 – 20 kPa, that corresponds practically to absence of a viscous component. Thus, the range of magnetic field induction to 300 mT is optimal from the point of view of magnitude of viscoelastic characteristics change.



a b

Fig. 6 Dependences of storage modulus and loss modulus of MRF on the basis of carbonyl iron particles and aerosil on deformation amplitude: *1* – *B* = 0, *2* – *B* = 50 mT, *3* – 100 mT, *4* – 200 mT, *5* – 300 mT, *6* – 500 mT, *7* – 700 mT, *8* – 1000 mT

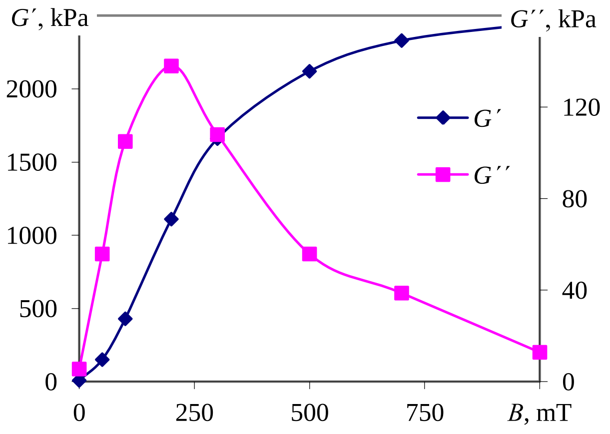


Fig. 7 Dependences of storage modulus *G*' and loss modulus *G*" of MRF on the basis of carbonyl iron particles and aerosil on magnetic field induction at the deformation *ε* = 0.01%

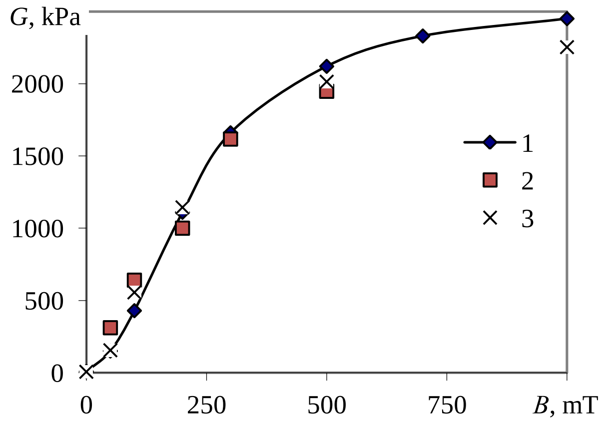


Fig. 8 Dependences of storage modulus MRF on magnetic field induction: *1* – storage modulus *G*', defined in mode of sinusoidal tangential oscillations, *2* – instant elasticity modulus G_1, defined from creep curves, *3* – elasticity modulus, defined from deformation curves slope

Let's compare the storage modulus *G*' received in that way to the instant elasticity modulus G_1 which is defined from creep curves as the ratio of the applied shear stress τ to deformation jump ε_1 in the curve beginning. It is obvious, that values are close, the results received by the different methods, are consistent (Fig. 8). Also it is possible to define the elasticity modulus from slope of deformation curves (Fig. 1) as the ratio τ/ε in the curve beginning, at small deformations in a range to 0.1%. Similarly, we have satisfactory accordance of results (Fig. 8). Thus, values *G* in the range of small deformations, received by three various methods, well agree.

4. Conclusions

The results of experimental investigation of rheological properties of high-concentrated magnetorheological two-component materials for layered structures in various modes have shown essential change of characteristics under external magnetic field influence. So, shear resistance in the magnetic field with induction 1 T increases almost by two orders that provides a considerable control range of their viscoplastic properties. The contribution of instant elastic, retarded viscoelastic and irreversible viscous deformation in creep mode is defined. The experimental results received in a mode of sinusoidal tangential oscillations prove possibility of application of magnetorheological material as an adaptive layer of layered constructions and shells, at optimum range of the magnetic field induction is to 300 mT.

Acknowledgement

This research is funded by the European Social Fund under the project "Smart mechatronic technologies and solutions for more efficient manufacturing processes and development of environment friendly products: from materials to tools (In-Smart)" (Agreement No. VP1-3.1-ŠMM-10-V-02-012).

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ADAPTYVIŲ MAGNETIŠKAI JAUTRIŲ MEDZIAGŲ, SKIRTŲ LAMINUOTOMS KOMPOZITINĖMS STRUKTŪROMS, TYRIMAS

Reziumė

Straipsnyje pateikti kelių dvikomponenčių magnetoreologinių medžiagų, skirtų naudoti laminuotų kompozitinių struktūrų sluoksniams, reologinių savybių tyrimo rezultatai. Ištirta valkšnumo režime dirbančios magnetoreologinės medžiagos structūrinio-reologinio reagavimo kinetika, nustatyti medžiagų elastiškumo ir nuostolių moduliai.

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INVESTIGATION OF ELASTICITY OF MAGNETO-SENSITIVE ADAPTIVE MATERIALS FOR LAMINATED COMPOSITE STRUCTURES

Summary

The results of investigation of the rheological properties of series compositions of two-component magnetorheological materials for use as layers of composite structures are presented. The kinetics of structural-rheological response of the magnetorheological material in creep mode is studied, elastic and loss moduli of materials are defined.

Keywords: adaptive magnetorheological material, rheological properties, viscoelasticity, control range.

Received February 05, 2014
Accepted September 17, 2014