Elastic and strength properties of metal rubber material

Alexander Aleksandrovich Troynikov, Yurii Andreevich Moskalev

Samara State Aerospace University
Russia, 443086, Samara, Moskovskoye Shosse, 34

Abstract. MR material is a porous structure obtained by cold pressing of blanks from metal spiral into elastic elements finished by shape and size, which further will be formed into vibration isolators. The application efficiency of vibration isolators based on the MR material in the vibration isolation systems is mainly determined by its elastic and strength properties. This paper deals with experimental work, the relationship between technological and operational parameters is based on the similarity theory and dimensional analysis. The results of the study for practical use are obtained in closed form.

Keywords: elastic element, vibration isolator, dimensional analysis, strength, elasticity.

Introduction. Mechanical properties of the MR material can be studied by microscopic method, based on a detailed study of individual elements and their interactions, as suggested by A.M. Soifer and his followers [1, 2, 3]. In the case of resolving this problem we will be able to create a physical model and write the equation of state of an interacting elements system. This approach, based on the study of elementary processes, can give us full details on the metal rubber properties. However, there is currently no reliable data on the behavior of the individual elements, the nature of their interaction, therefore, no mathematical statement of the problem.

In such cases, use of the macroscopic approach may be appropriate, which does not consider the interaction of the individual elements, and only integral side of processes is fixed. The data obtained can serve as a basis for theoretical studies. If it turns out that the dependences obtained are valid only in relation to the products class considered, then the transition to other classes can be done based on similarity theory and dimensional analysis, which are the only possible theoretical method at the initial phase of the study of material properties.

Since the microscopic approach is not able to lead to a satisfactory physical model and mathematically relate the initial parameters of the MR products with their basic mechanical properties, the objective shall be achieved by macroscopic approach [4]. Macroscopic approach allows setting and accumulating patterns, which reflect the behavior of material while its cyclic deformation, and which, can be used for creating a physical model after their appropriate ordering.

Technique. The process of loading the MR material is accompanied by elastic and plastic deformation of the elements and their mutual sliding. After removing the load, elements tend to occupy the original position under the action of elastic forces, but their initial position changes, resulting in residual deformation. As the number of "load-unload" cycles grows, there is an increase and a decrease in the permanent Y_0 and reversible Y deformations, respectively. After a certain number of cycles n_Γ, depending on the structure of the material and strength of the loading P, the relation between the components of the total deformation is stabilized (see Fig. 1, where $\overline{Y} = \dfrac{Y}{H_C}$; $\overline{Y}_0 = \dfrac{Y_0}{H_C}$, $H_c -$ height of elastic-damping element in a free (unloaded) state).
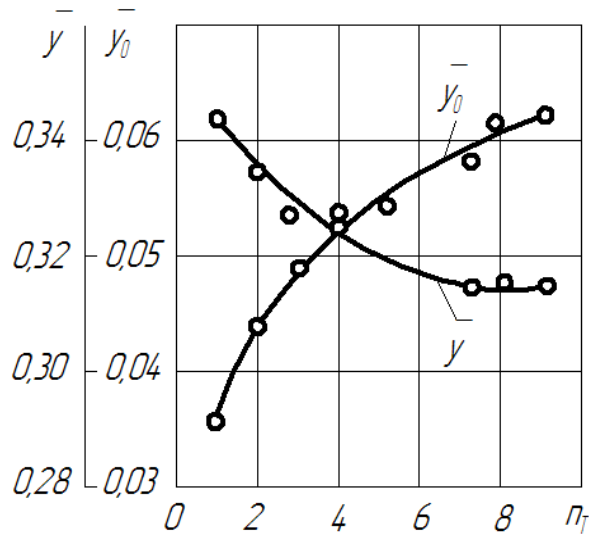
Fig. 1. Change of the components of total deformation of elastic-damping element during practicing
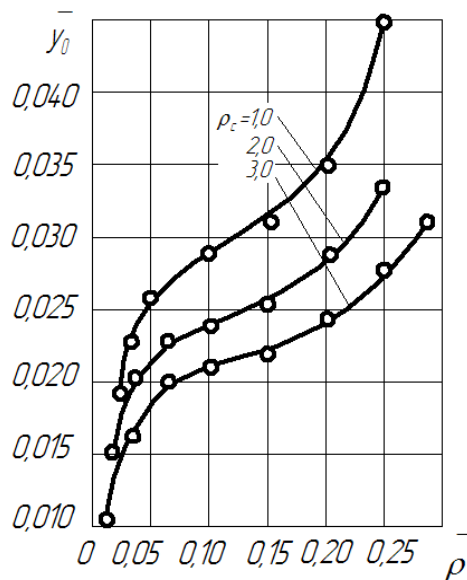

Fig. 2. The dependence of elastic-damping element shrinkage on the relative strength of loading at different MR densities.

The permanent deformation occurs due to the presence of friction forces between elements, plastic deformations of individual elements or groups and the change of their mutual arrangement (re-orientation). Fig. 2 shows the dependence of relative permanent deformation on the relative strength of loading $\left(\overline{\rho} = \dfrac{P}{P_{\Pi P}}\right)$,

$P_{\Pi P}$ – EDE pressing force) at different densities of the material ρ_c. Reversible deformation was estimated by the difference between total and residual components. Figure 3 shows behavior of permanent deformation y depending on total deformation y_{Π}. The dependences shown in Fig. 3 are valid for the sample with fixed values of process parameters and dimensions.
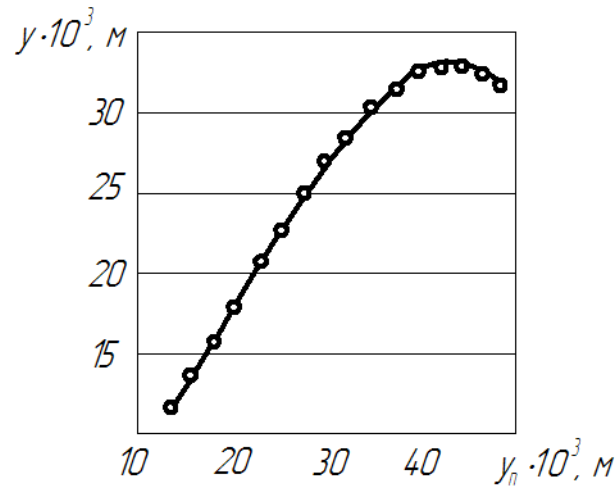
Fig. 3. Behavior of permanent EDE deformation depending on total one.

To find the dependence of the maximum deformation on the material parameters we have tested the specimens in the form of a cylinder, a sleeve, a cube and prism. After selecting parameters defining the elastic properties of the material, the equation for the maximum value of reversible EDE deformation can be written as follows:

$$Y_H = \varphi_1\left(\rho_C, \rho_3, \rho_И, d, \delta, t_C, \sigma_{TИ}, E_И, H_C\right) \tag{1}$$

Equation (1) contains ten variables, is homogeneous in relation to dimensions, therefore, it can be expressed through the immense combinations of its values by applying the first part of the π-theorem [2]. If we take mass, time and length as the basic units, we shall obtain seven dimensionless ratios on the basis of the second part of π-theorem:

$$\frac{Y_H}{H_C} = \varphi_2\left[\left(\frac{\rho_C}{\rho_И}\right)^a \left(\frac{\rho_3}{\rho_И}\right)^b \left(\frac{\sigma_{TИ}}{E_И}\right)^c \left(\frac{d}{\delta}\right)^d \left(\frac{t_C}{\delta}\right)^e \left(\frac{t_C}{H_C}\right)^f\right] \tag{2}$$

As follows from the analysis of the impact of dimensionless ratios on the value of relative reversible deformation (see Fig. 4), the complexes containing a variable t_C (spiral stretching pitch), have a slight effect on the change $\dfrac{Y_H}{H_C}$, and therefore are excluded from the equation. Considering the EDE processability, the spiral stretching pitch is taken to be equal to its outer diameter. After solving an equation (2) in relation to each complex and determining a matching constant at their fixed values $\overline{\rho}_C = \dfrac{\rho_C}{\rho_И} = 0,25$;

$$\overline{\rho}_3 = \frac{\rho_3}{\rho_И} = 0,062;$$

$$\overline{\sigma}_{TИ} = \frac{\sigma_{TИ}}{E_И} = 0,006; \, d = 10, \text{ we shall write the final result:}$$

$$Y_H = 31\overline{\sigma}_{TИ} H_C\left(0,64 - \overline{\rho}_C\right)\left(0,2 - \overline{\rho}_3\right)\left(20 + \overline{d}\right) \tag{3}$$

The analysis of equation (3) shows that the value of reversible deformation is mainly affected by the material density. The change of $\overline{\rho_C}$ from 0.12 to 0.37 leads to the same of $\overline{y}_H = \dfrac{y_H}{H_C}$ from 0.55 to 0.29. The influence of other parameters is much weaker.
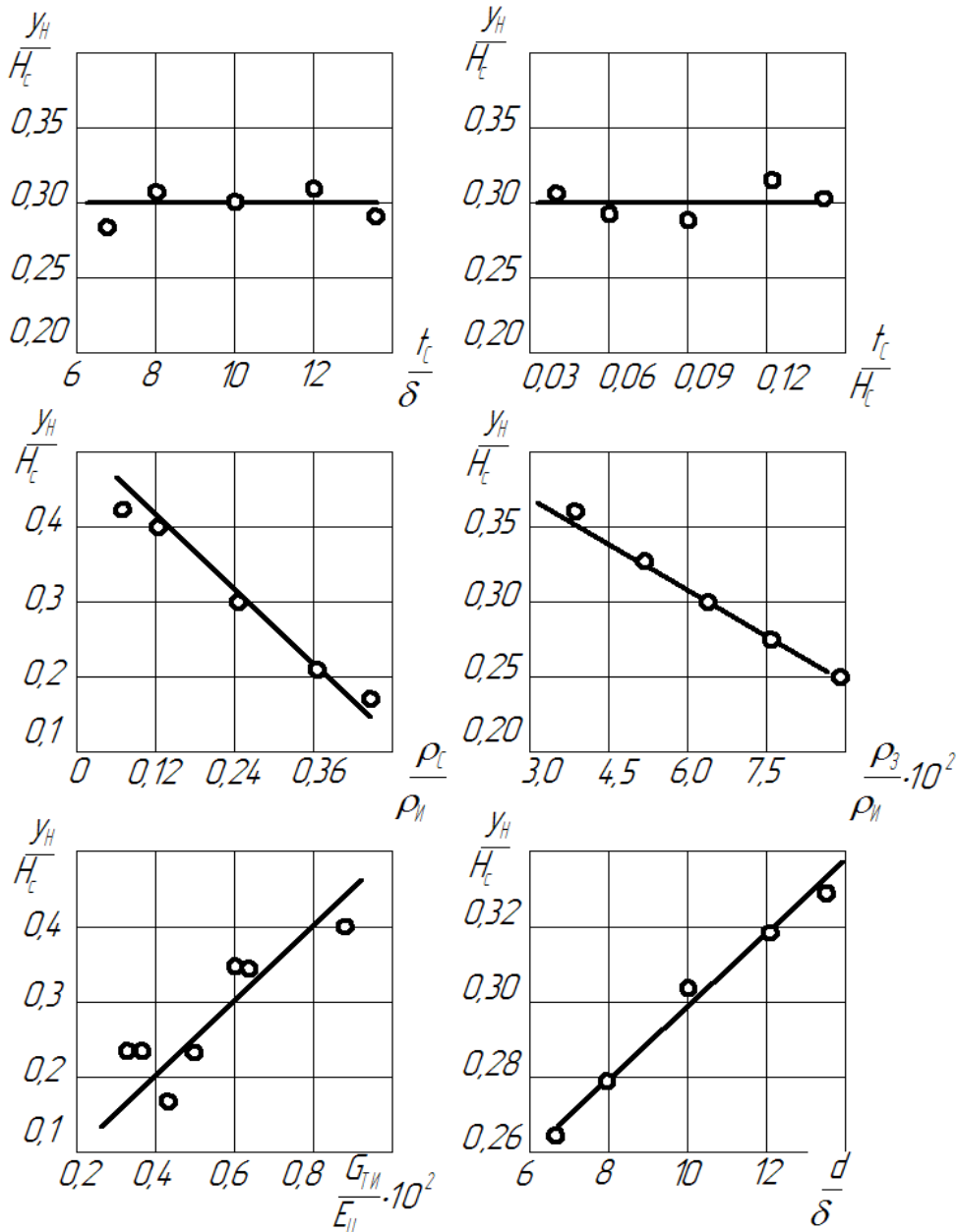

Fig. 4. Dependencies of the EDE relative reversible deformation of the dimensionless parameters of the MR material

Maximum reversible deformation of the MR material during compression determines its elastic limits, and the power causing the maximum deformation is taken as the critical loading force ρ_{KP}.

Strength properties of MR can be evaluated by strength limit, which is the ratio of the critical load power to the cross-sectional area of the undeformed specimen. Exceeding the strength limit leads to the destruction of EDE.

Magnitude of critical force depends on the technological parameters of the MR and the geometric dimensions of EDE. Application of the dimension theory can both reduce the number of variables that determine the strength of the material, and make a dimensionless complexes in such a way as to reflect their physical meaning in the most appropriate form.

After selecting the parameters determining the strength properties of the material, we can write the equation for the critical loading force:

$$P_{KP} = \varphi_3 \left(\rho_C, \rho_3, \rho_B, E_И, \sigma_{TИ}, S \right), \qquad (4)$$

where ρ_B – coil density.

Applying the Rayleigh method for the solution of the dimensional systems, we shall express the equation (2.4) in terms of dimensionless complexes:

$$\frac{P_{KP}}{SE_И} = \varphi_5 \left[\left(\frac{\rho_C}{\rho_3} \right)^a, \left(\frac{\rho_B}{\rho_3} \right)^b, \left(\frac{\sigma_{TИ}}{E_И} \right)^c \right].$$

The complex $\overline{P}_{KP} = \dfrac{P_{KP}}{SE_И}$ is the strength limit related to the elasticity modulus of the wire material; simplex $\overline{\rho}_0 = \dfrac{\rho_C}{\rho_3}$ characterizes the compaction degree of the material during compression (axial compaction); simplex $\overline{\rho}_P = \dfrac{\rho_B}{\rho_3}$ is a coil compaction during the workpiece formation (radial compaction); complex $\overline{\sigma}_{TИ} = \dfrac{\sigma_{TИ}}{E_И}$ represents the elastic properties of the wire material. After determining the matching constant at the values of complexes $\overline{\rho}_0 = 4,0$, $\overline{\rho}_P = 0,654$, $\overline{\sigma}_{TИ} = 0,006$, we shall write the final result:

$$\sigma_{BУ} = 0,65 \cdot 10^{-5} \sigma_{TИ} \left(\frac{\rho_C}{\rho_3} \right)^2 \left(11,2 - \frac{\rho_B}{\rho_3} \right)^2.$$

Strength of the MR material during compression depends on the yield limit of the wire material, as well as the axial and radial compaction of the workpiece.

The application range of MR-based vibration isolators is mainly determined by their elastic and strength properties. That is why it is very important to identify and eliminate causes, which narrow down the operating range of the material, when developing new isolator designs.

The cause, which narrow down the application area of MR-based vibration isolators, is nonuniformity of structural stresses on the EDE volume. When determining the strength properties of the MR-based products, the average stresses typical for a continuum were considered rather than local stresses associated with structural features of the material.

The MR material has at least two types of nonuniformity of structural stresses. Nonuniformity of the first type is caused by the inhomogeneous distribution of the spiral in the workpiece volume and is determined by EDE manufacturing quality. The influence of the structural nonuniformity on the strength of the material is especially noticeable in the case where the dimensions of a single element of spiral coil are commensurate with the dimensions of the finished product. This structural defect can be eliminated by improving the EDE manufacturing quality or using a smaller diameter wire.

The second type of nonuniformity of the structural stresses is associated with the nonuniform distribution of the density in the height of the elastic element. This ability of the material affects significantly its strength, since areas with the lowest density are the first to undergo the destruction. We shall consider this type of structural nonuniformity in details.

Elastoplastic deformation of the workpiece in a mold is accompanied by a reorientation of the coils and, as a result of their "propping" action, increase in the pressure on the walls of the mold. The contact friction force of the workpiece and a mold reduces the magnitude of the effective compression force.

The effective compression force and EDE density may be associated with its form factor

$$\Phi = \frac{S_3}{S_\delta},$$

where S_3 – area of the workpiece base;

S_δ – area of the side surface of the workpiece.

Fig. 5 shows the experimental dependencies of the relative values of the maximum and minimum EDE densities on the its compaction degree during compression for different values of the form factor.
These dependencies can be expressed analytically:

$$\frac{\rho_{\max}}{\rho_C} = 1 + \frac{4,53 \cdot 10^{-3}}{\Phi} \left(\overline{\rho}_0 - 1 \right)^{1,918} e^{-0,52\left(\overline{\rho}_0 - 1 \right)};$$

$$\frac{\rho_{\min}}{\rho_C} = 1 - \frac{1.06 \cdot 10^{-3}}{\Phi} \left(\overline{\rho}_0 - 1 \right)^{2,535} e^{-0,542\left(\overline{\rho}_0 - 1 \right)};$$
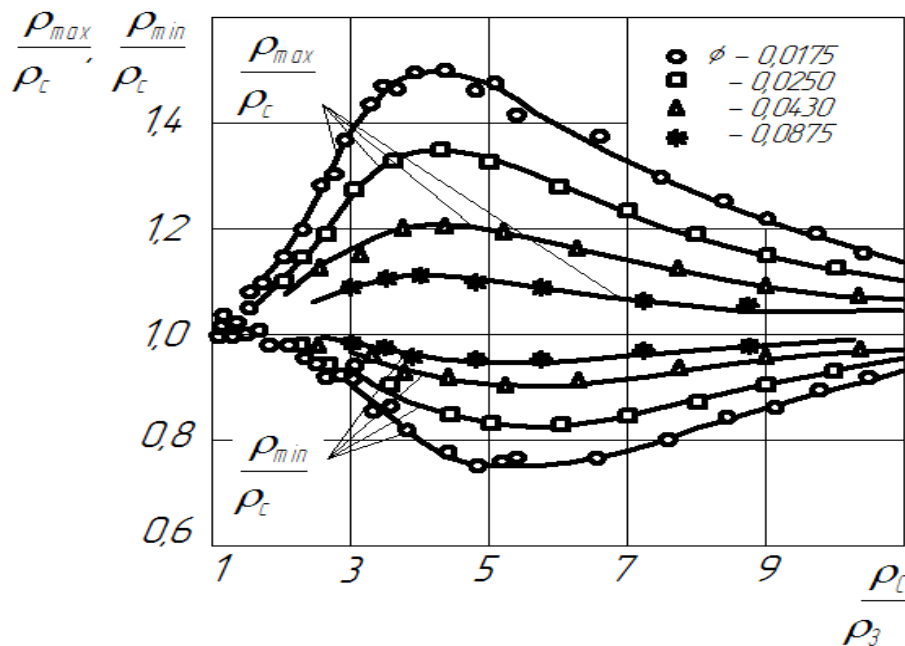

Fig. 5. Influence of the form factor on the distribution of the density in EDE height for different MR compaction degrees

At low compaction degrees, the friction force is virtually constant in the workpiece height, and the material is mainly pressed due to the mutual introduction of spiral coils. Increasing the pressing force causes a rotation and laying of coils in a plane perpendicular to the direction of the pressing force. The pressure on the walls of the mold and the frictional force increases, and the effective compression force decreases, as moving from the movable die.

At higher degree of density $\left(\overline{\rho}_0 \geq 5 \right)$ the heterogeneity of workpiece density decreases throughout the height. The reason probably lies in the fact that the orientation of the coils becomes stable, while the friction force of the material against the walls of the mold, as in the initial stage of compression, tends to a constant value, which promotes a more uniform density distribution through the workpiece height. When determining the permissible loads on the elastic element, the density of the material is taken as the minimum one, found from the second equation.

Another reason that determines the EDE operating range is the value of the maximum reversible deformation. The drive to maximize the reversible deformation leads to a decrease in the workpiece density and MR compaction degree during the compression. However, low density of workpieces results in increasing the sensitivity of the material to a manufacturing method (a significant change in properties even with minor deviations from the technology). Small values of the material compaction during pressing require a particularly careful handling of goods during transportation, storage and assembly of the vibration isolator.

Uncertainty of the impact of technological and operational factors on the characteristics of the EDE prevents to conclusively determine their role in the expansion of the elastic capacity of the material. In cases where it is not possible to calculate the operational range, the safety factor is introduced. As experience shows, the value of the assurance coefficient varies for the reversible deformation during compression of MR material between 1.1-1.2, and depends on the level of automation and control of the intermediate operations when manufacturing the EDE. Currently, a more rigorous substantiation does not seem possible.

Conclusion. Investigation of elastic and strength properties of metal rubber material was carried out assuming that the object of study is presented as a continuum. Therefore, the determination of the mechanical properties of the material was based on the similarity theory and dimensional analysis. The analytical dependences obtained can be used in the calculation of vibration isolators subject to specific operating conditions. We have determined factors limiting the elastic and strength capabilities of the MR material, which are of practical importance in determining the application range of the vibroisolating products.

Discussion. The obtained analytical dependences of the elastic and strength properties of the MR material on the technological parameters of the material, are only limited by practical application during the calculation of vibration isolators. The results shall not apply to research related to changes in the mechanical characteristics of the MR material for the elastic-damping elements having a complex geometric shape and undergoing a complex stress state [5, 6]. An approach based on the study of the elementary processes of interacting elements that make up the structure of the MR material may be effective.

REFERENCES

[1] Ponomarev, Yu.K., Ermakov A.I., Simakov O.B., Mikhalkin I.K. Metallic counterpart of rubber: a material for vibration and shock protection. Metallovedenie I termicheskaya obrabotka metallov. # 1 (691). January, 2013. PP 8 – 13 / doi: 10.3103/S1068799809020111.

[2] Jiang, H.-Y., Hao, D.-G., Xia, Y.-H., Ulanov, A.M., Ponomarev, Y.K. Damping characteristics calculation method of metal dry friction isolators (2008) Journal of Beijing Institute of Technology (English Edition) 17 (2) PP. 173 – 177 / doi: 10.3103/S1068799809020111.

[3] Xia, Y., Yan, H., Jiang, H., Ao, H., Ulanov, A.M. Determination of elastic modulus of ring-like metal rubber isolator (2005) Run Hua Yu Mi Feng/Lubrication Engineering (3) PP. 34 - 36+39 Cited 6 times.

[4] Ao, H., Jiang, H., Ulanov, A.M. Dry friction damping characteristics of a metallic rubber isolator under two-dimensional loading processes (2005) Modelling and Simulation in Materials Science and Engineering 13 (4) PP. 609 - 620 Cited 11 times / doi: 10.1088/0965-0393/13/4/011.

[5] Ao, H., Jiang, H., Wang, S., Xia, Y., Ulanov, A.M. Dry friction damping characteristics of Metallic Rubber (MR) isolator with 2-D loading process (2003) SAE Technical Papers / doi: 10.4271/2003-01-1470.

[6] Ao, H.-R., Jiang, H.-Y., Yan, H., Xia, Y.-H., Ulanov, A.M. Research of a metal rubber isolation system based on complex stiffness (2005) Harbin Gongye Daxue Xuebao/Journal of Harbin Institute of Technology 37 (12) PP. 1615 - 1617+1693.