Optimization of the rubber element of the rubber-metal hinge of a tracked system

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Abstract. The paper presents the formulation of the problem of optimal design of rubber bush of the track link and its solution. The search for the optimal design is based on the results of calculating the stress-strain state of the rubber ring caused by the assembly of the rubber-metal hinge and loads during subsequent operation. As an objective function, the specific energy of deformation of the rubber was chosen. The dimensions of the rubber ring of the rubber-metal hinges in the undeformed state are taken as variable parameters. Formulation of the optimization problem imposes constraints on the design parameters in the form of inequations.

The solution of the problem of optimal design and the results of durability tests are presented.

1. Introduction
A tracked system is a complex multi-mass system whose components are subjected to high dynamic loads during machine movement [1, 2], which leads to a reduction in their durability. The high dynamic loads are caused both by the principal design of the tracked system and by the interaction with the track surface. One of the design disadvantages of the tracked system is the open metal hinges for connecting the chain links, which are subject to intensive wear during operation. To reduce the dynamic loads and wear of the track chain hinges, rubber-metal hinge connections are used to connect the adjacent tracks of the tracked system [3 - 6]. The applied rubber-metal hinges with power rubber elements have a sufficiently high load-carrying capacity and can significantly increase the durability of the caterpillar chain.

Rubber-metal hinge connections can be of three types: welded, prefabricated, and combined. In welded hinge designs, the rubber is rigidly connected to the metal fitting on the outside and inside diameter during vulcanization. In prefabricated hinges, the rubber elements are pressed onto the metal pin and pressed into the bore of the metal sleeve. When the hinge is tightened, the rubber is kept from moving relative to the surface of the pin and the surface of the covering metal sleeve by frictional forces resulting from the pressure in the rubber-metal contact. The feature of the combined hinge design is that the rubber is rigidly connected during vulcanization only to the metal of the covering sleeve or to the metal of the pin. After vulcanization, the rubber-metal element is pressed onto the pin or pressed into the eyelet hole.

The rubber elements of the hinge connection of track of tracked system of high-speed tracked vehicles take all the load acting on the hinge, which causes large deformations of rubber elements in the radial direction and leads to their low durability.
To reduce the effect of radial loads on the elastic elements of the hinge, a design with a radial deformation limiter is used (Figure 1), which makes it possible to significantly increase the durability of rubber elements of the hinge.

Figure 1. Rubber-metal hinge compound of the track chain links:
1 – pin; 2 – limiter of radial deformation; 3, 4, 5 – rubber elements; 6 – tracks.

2. Research method
High requirements are imposed on the design of the caterpillar chain to ensure strength properties while striving to reduce their weight [7, 8]. During operation, the elements of a tracked system are subject to wear, which leads to a decrease in their strength and stiffness, therefore, when designing the tracked system elements, it is necessary to provide the required reserve taking into account wear. Conflicting requirements for the design of the track system with rubber-metal elements force to apply optimization methods in the design of the hinge connection.

This paper presents the formulation of the problem of optimal design of rubber elements of the hinge, which connects the links of the caterpillar chain, as well as the results of its solution. When choosing the design parameters of rubber-metal hinge connection it is necessary to ensure, on the one hand, the maximum durability of rubber and metal elements of the hinge connection and, on the other hand, to reduce the dynamic loads in the track chain due to the characteristics of angular, radial stiffness and damping properties of the hinge connection. Radial and angular stiffness as well as the damping properties of the track chain hinge connection are provided by the design parameters of the rubber hinge elements after assembly.

The inside and outside diameters of the rubber element after assembly are determined by the diameter of the eyelet hole and the pin. The width of the rubber ring is determined by the dimensions in the original undeformed state. Varying the above geometric parameters for the hinge connection of the same overall size makes it possible to change the hinge stiffness characteristics in a wide range, which makes it possible to search for optimal hinge parameters for a particular tracked system design without significantly increasing the dimensions. It should also be noted that the shape of the rubber element in the initial undeformed state of the rubber element has no significant effect on the hinge stiffness characteristics.

The track chain with a rubber-metal hinge (Figure 2) was tested for durability as part of the product.

Figure 2. Track and pin of the rubber-metal hinge of tracked system.

The rubber elements of the hinge connection (Figure 2) have a trapezoidal cross-section in an undeformed state. As the results of durability tests of the rubber-metal hinge show, the rubber element begins to collapse at the contact boundary between the rubber element and the surface of the eyelet.
hole (Figure 3). In the first stage, there are traces of fatigue wear at the contact area boundary resulting from the rubber sliding against the surface of the eyelet. In the later stages of the test, fatigue cracks form in this area. The appearance of fatigue cracks is caused by cyclic repeated loads on the rubber elements of the hinge during the operation of the tracked vehicle, which causes the concentration of specific strain energy in this area [7, 8]. The simultaneous action of these two factors on the material of the rubber element at the border of contact with the metal of the eyelet is the main reason for the destruction of the rubber elements in this area.

![Figure 3. Fatigue failure of rubber elements with trapezoidal cross-section.](image)

The results of durability tests of rubber-metal hinge connections of the tracked system, design principles developed by practice, as well as the developed methods of calculating their stress-strain state based on the relations of nonlinear elasticity theory allow us to formulate the requirements for the design of rubber elements and setting the problem to find their optimum shape, which ensures maximum durability [7].

The design of a rubber-metal hinge connection is subject to severe constraints that must be taken into consideration. The rubber elements must be placed in the track link eyelet hole and not touch the limiter. During hinge assembly, the rubber element is subjected to shear deformation by frictional forces, and it is necessary to prevent the rubber element from entering the gap between the limiter and the eyelet, as this would cause the rubber element to collapse. When pressed in, the rubber must not be allowed to run over the metal pin as this leads to intensive fatigue wear of the rubber element and there must be no possibility of abrasion between the surface of the eyelet hole of the track and the rubber element. One important parameter that affects the performance of the rubber element in the hinge is the contact pressure between the rubber and the eyelet hole. It must not only prevent the rubber element from turning in relation to the surface of the eyelet but also prevent the rubber from sliding against the metal throughout the contact. To ensure the necessary pressure, it is possible to increase the degree of pressing. In turn, increasing the degree of pressing worsens the conditions of the hinge assembly, causes damage to the rubber element and increases tangential stresses $\tau_z$, which should be less than the allowable values. There are also requirements for the angular and radial stiffness of the rubber element, which affects on the dynamic loads in the caterpillar chain.

3. Theory

Experimental and theoretical studies have shown that dependences based on energy criteria are used to assess the durability of rubber elements under the mechanical impact of cyclic nature [9 - 11]. In the present work, the specific strain energy is used as a criterion determining the cyclic durability of rubber. When moving along the track perimeter, the rubber elements of the hinge are subjected to the highest loads when the hinge is positioned on the working branch of the tracked system. When the hinge enters the arc branch on the drive wheel, the maximum radial force acts on the hinge and the hinge is twisted when the link is placed on the drive wheel. For this mode of loading, the stress-strain state of rubber elements is calculated and the specific strain energy is determined. It is taken into account that the rubber element is in the deformed state caused by its pressing into the eyelet hole. The finite element method is used to solve the stress-strain state problem. Rubber is considered as an
incompressible material, and its mechanical properties are described using the Treloar potential [8, 12, 13]. Improving the cyclic durability of rubber elements is associated with the search for such design parameters that will minimize the maximum value of the specific strain energy under secondary loading by radial force and torque, and will ensure that the rubber does not slide against the eyelet hole throughout the entire contact.

In this paper, when searching for the optimal design of the rubber element, the value of the maximum value of the specific potential energy of deformation caused by the secondary loading of rubber elements during the operation of the tracked vehicle is taken as the target function. The design parameters $x_j$ are coordinates of points $P(r; z)$ on the contour of the section, which define the design of the rubber element before the pressing in the initial undeformed state (Figure 4). The mathematical formulation of the optimization problem is as follows: find vector $\vec{x}$, at which the target function takes the minimum value

$$Z = \min_{\Omega} \left[ \max_{\Omega} (W) \right],$$

where $\Omega$ is the cross-sectional area of the element with varying boundary $\Gamma$. Constraints on the design parameters are given by a system of inequalities:

$$x_j^- \leq x_j \leq x_j^+, \quad (j=1, 2, \ldots, m),$$

where $x_j^-$, $x_j^+$ are the limits of variation of the components of the vector $\vec{x}$; $m$ is the number of independent design parameters.

![Figure 4. Design parameters defining the design of a rubber element.](image)

The functional constraints on the design parameters are given by a system of inequations:

$$\sigma_r - [\sigma] > 0 ;$$
$$\max_{\Omega} [\tau_r] - [\tau_r] < 0 ;$$
$$K_{r_{\min}} \leq K_r \leq K_{r_{\max}} ;$$
$$K_{\phi_{\min}} \leq K_\phi \leq K_{\phi_{\max}} ,$$

where $\sigma_r$ is the rubber pressure on the surface of the eyelet hole in the contact area; $\tau_r$ is the tangential stresses from pressing; $K_{r_{\min}}$, $K_{r_{\max}}$ are the lower and upper limit of radial stiffness; $K_{\phi_{\min}}$, $K_{\phi_{\max}}$ are the lower and upper limit of angular stiffness.
The objective function (1) and functional constraints (3) are determined as a result of solving the problem using the finite element method, so to solve the optimization problem the complex Box method is used [14, 15].

4. Calculation results
As a result of solving the optimization problem, the design parameters of the rubber element of the rubber-metal hinge of the caterpillar chain were obtained. Figure 5 shows a cross-section of the rubber element in the initial undeformed state. The shape of the section is a trapezoid with curved sides and a concave upper base.
The specific strain energy caused by operational loads for the optimal shape of the rubber element cross-section is shown in Figure 6. The destruction of the rubber elements of the hinge, which have a trapezoidal shape in the cross-section, begins with the nucleation of fatigue cracks at the boundary of the contact surface of the rubber element and the surface of the eyelet hole (Figure 3). The cause of fatigue crack initiation is the concentration of specific strain energy [7]. For a rubber element of optimal shape (Figure 5) there is no concentration of specific strain energy in this area (Figure 6, area 2), its value in this area does not exceed 0.037 MJ/m³.

![Figure 5](image1.png)

**Figure 5.** Cross-section of an optimally shaped rubber element.

In addition, tangential stresses $\tau_{\theta}$ in the contact area of the surface of the rubber element with the surface of the eyelet throughout the contact are much less than the contact pressure $\sigma_r$, which eliminates the possibility of sliding of the rubber against the surface of the eyelet. Thus, in the area of rubber destruction, the influence of wear on the durability of rubber element is excluded, the specific strain energy is considerably reduced in comparison with areas 1 and 3 (Figure 6) in which it reaches the maximum values of 0.102 MJ/m³.

![Figure 6](image2.png)

**Figure 6.** Specific strain energy when twisting the rubber element.
With simultaneous loading by radial force and twisting of the rubber element, which is typical for the operation of the hinge connection on the leading section of the caterpillar chain, the specific strain energy reaches its maximum value in area 1 (Figure 7) and reaches 0.245 MJ/m³. In area 2 its value also increases and reaches 0.160 MJ/m³. The combined effect of twisting of rubber element and loading by radial force leads to an insignificant increase of specific strain energy in area 3 which does not exceed 0.113 MJ/m³.

5. Experimental results
The durability tests of the rubber power elements of the hinge connection were carried out on a special test bench which allows the rubber elements of the hinge to be cyclically subjected to radial load and twist at a defined angle. The radial load and twist angle of the hinge are provided by the kinematic parameters of the stand. The rubber elements were twisted to an angle $\pm 7.5^\circ$ and subjected to cyclic radial deformation varying per cycle from 0 to 0.5 mm. The specified conditions are characteristic of the operation of the rubber-metal hinge connection of the caterpillar chain in the driving section of the tracked system, namely during the laying of the link on the drive wheel.

Rubber elements with different design parameters, but with the same radial and angular stiffness, were subjected to durability testing. One rubber element had the design parameters obtained by solving the optimization problem. The design of the second rubber element corresponded to the rubber elements of the rubber-metal hinge of the tractor caterpillar chain, which showed the longest durability as a result of field tests.

Figure 8 shows a photograph of the rubber elements of the hinge after $N = 6.8 \cdot 10^6$ cycles. Damage to the trapezoidal rubber element (Figure 8, item 1) is fatigue cracking along the edge of the rubber contact surface with the surface of the eyelet hole. There is no damage to the surface of the rubber element whose design has been optimized (Figure 8, item 2).
The durability of the rubber elements, the design parameters of which were obtained as a result of solving the optimization problem, was $N = 10.5 \cdot 10^6$. The state of the rubber elements after the test is shown in Figure 9. The destruction of rubber element has begun in the area of concentration of specific strain energy caused by combined cyclic loading of radial force and torque (Figure 7, area 1).

![Figure 9](image)

**Figure 9.** Condition of the rubber elements of the joint after tests ($N = 10.5 \cdot 10^6$ cycles).

6. **Conclusions**

The search for optimal design parameters of rubber-metal hinge connection of the caterpillar chain links carried out within the framework of the formulated optimization problem and based on the results of calculation of the stress-strain state of rubber elements, carried out with the help of the direct search algorithm, namely, the complex Box method, allowed: to ensure that the rubber does not slide against the surface of the eyelet hole throughout the entire contact, thus avoiding destruction at the extreme points of the contact due to fatigue wear; to eliminate the concentration of specific strain energy at the extreme points of the rubber element’s contact area with the surface of the eyelet hole. The durability tests of the rubber elements of the hinge connection of the caterpillar chain for durability have confirmed that: the elimination of the combined effects of fatigue wear and the concentration of specific strain energy in a single area can increase the durability of rubber hinge components; failure of rubber elements, the design of which is obtained by optimization, occurs in the area of concentration of specific strain energy caused by secondary loading by radial force and torque.

7. **References**

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