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Substantiation of parameters of metal structure elements of mining transport machines

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Abstract

The relevance of the work is due to the need to reduce the metal consumption of mining vehicles while maintaining the strength characteristics of their metal structures. An effective tool for finding the best option for combining the design parameters is optimization theory from the point of view of obtaining the design with the required properties. The implementation of the principles and approaches of this theory in relation to the metal structures of mining transport vehicles allows achieving a combination of their geometric characteristics, which makes it possible to obtain the smallest mass and dimensions.

Purpose of the work: development of the principle of obtaining mathematical dependencies, allowing to determine the most suitable shape and size of the cross section for the elements that make up the metal structures of mining vehicles, taking into account the direction of the loads perceived by each element.

Research methodology. An optimization approach is used, including the definition of the design parameters, the formulation of the objective function and the restrictions imposed on the design parameters.

Results and their application. The factors affecting the value of the optimal parameters in the elements of the metal structures of mining vehicles are established. The optimal parameters of the cross section are substantiated for various combinations of the perceived load direction and the priority requirements for metal construction. The obtained recommendations can be applied in the design of frames with a minimum weight or dimensions.

Conclusions. The recommendations presented allow us to reasonably choose the best cross-sectional shape of the metal elements of mining transport vehicles, depending on the direction of the current loads. The requirements for metal construction, such as minimum metal consumption and (or) surface area, are taken into account. For rods working in tension or compression, the most rational is the square shape of the cross section. For bending elements, a rectangular section with a height/width ratio of two is best suited. These conclusions are drawn from considerations of the least metal consumption and the smallest surface area of the metal structure. Taking the proposed recommendations into account when designing the metal structures of mining transportation machines will allow us to obtain the lowest values of metal consumption, and, consequently, the cost of the machine with the required technical characteristics.

Keywords: mining vehicles, design, optimization, parameter, metal structure, cross section, surface, objective function.

Introduction

To date, more than half of all minerals are mined by open-pit mining, and this indicator has a tendency to constant growth. Among the minerals mined in quarries, 100% of refractory and flux materials, almost all building materials. Open-pit mining of 75% of mining and chemical raw materials, 50% of ores of radioactive, rare and non-ferrous metals, 60% of ores of ferrous metals and 70% of coal. At the same time, the development of mineral reserves at great depths begins. This leads to an increase in the size of quarries and the complication of natural-technological conditions for development. At all development stages of such deposits, a comprehensive mechanization of mining using the most advanced engineering achievements is necessary.

Currently, Russian mining enterprises operate about 180 mechanical shovels of domestic production from the IZ-KARTEKS and PJSC Uralmash plants with buckets with a capacity of 12–32 m³, as well as about 20 excavators with 35–55 m³ buckets [1–3]. Beside, about 300 open pit hydraulic excavators with 12–45 m³ buckets from foreign companies Komatsu Mining Germany (KMG), Liebherr, Hitachi, Caterpillar, P&H, Taiyuan HM Group are also used [4, 5]. The capacity of commercially available dump trucks has reached 360 tons [6].

As a rule, mining vehicles are operated in very difficult conditions. They are exposed to corrosive environments, cyclic, dynamic and static loads, low and high temperatures, and

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most often a combination of all these factors. All these factors inevitably affect the metal structure of the mining transport machine. This leads to the need to ensure high reliability of metal structures. On the one hand, such indicators can be achieved due to large safety factors, which reduces the risk of machine failure. But on the other hand, this approach leads to an increase in metal consumption, a decrease in specific power and an increase in the machine cost, which negatively affects its competitiveness.

Modern approaches in the field of mechanical engineering of mining transport machines set the goal of designing any technical objects and creating structures that simultaneously meet the requirements of maximum efficiency and minimum cost. However, solutions to the same technical problem by different designers can significantly differ.

The variety of possibilities in the design of mining transport vehicles, on the one hand, provides freedom of design creativity, but, on the other hand, carries the risk of an unsatisfactory result. The consequence of this design approach is the absence of a guarantee that the created technical object will be better than analogues developed by other enterprises.

Thus, there is a need to search for the optimal design without going through a multitude of options. The solution to this problem is possible using the optimization theory, which is a combination of fundamental mathematical and numerical methods aimed at finding the best option from a variety of alternative ones [7–11].

Methodology

In relation to the design of metal structures for mining vehicles, the optimization problem, as a rule, comes down to determining their geometric parameters. Moreover, the design result is affected not only by the loads acting on the metal structure, but also by the choice of the objective function that describes the output parameter of the system. Since any mining transport machine contains the main links, as a rule, representing the metal structure, which receives loads, acting in different directions, the urgent task is to make a reasonable choice of the cross section shape and size of the metal structure elements [12, 13].

A fairly common cross-sectional shape of the structural elements of mining vehicles is a solid or hollow rectangle (box section).

So, for example, the spinal beam of the lower frame of the dump truck (dump car) has a box section. When the car moves, it perceives shock and traction forces. Inside the spinal beam is an automatic coupler.

The frame of a heavy-duty mining dump truck also consists of two spars - longitudinal box-shaped beams, which are interconnected by cross members. The dump truck body is a welded structure, which is based on the side members and cross members with a box-shaped structure.

Box sections have belts of the rear wall of a mining excavator bucket; they absorb significant dynamic scooping forces. The handle of the excavator is a metal structure, which consists of two beams of rectangular cross section, interconnected in front of the transverse insert. The boom body also has a box section and is made of sheet metal [14, 15].

Elements of a hollow or solid rectangular section are also found in the metal structures of drilling rigs, bulldozers, conveyors, etc.

As an example, we determine the optimal parameters of a rod with a rectangular cross-sectional shape under the action of transverse forces and bending moments on it.

The following parameters act as input data for the calculation: M_{bend} – bending moment in a dangerous section of the rod; $[\sigma_{\text{bend}}]$ is the permissible bending stress, depending on the rod material.

In this case, the design parameters are b – section width, h – section height.

For comparison, two different objective functions can be proposed.

The first is the cross-sectional area of the rod. Minimization of this function will allow reducing the metal consumption of the structure:

$$S = bh \rightarrow \min. \quad (1)$$

Minimization of metal consumption is necessary, first of all, for mobile mining vehicles. For stationary machines, it is most important to reduce the metal consumption of the main links that are farthest from the fixed base of the machine.

The second is the rod half-perimeter. Achieving a minimum of this function, obviously, provides the minimum surface area of the rod and, therefore, the lowest consumption of materials applied to the rod, for example, paint or other coating:

$$P/2 = b + h \rightarrow \min. \quad (2)$$

The presence of a protective coating is especially relevant for the metal structures of mining transport vehicles operating under the influence of a corrosive environment. To a greater extent, protective coating is required by units that have been in direct contact with an aggressive substance for a long time.

Of course, an unlimited decrease in objective functions is impossible, since this will lead to the rod destruction under the action of given loads. This limitation is expressed by the strength condition:

$$\sigma_{\text{bend}} = \frac{M_{\text{bend}}}{W_{\text{bend}}} \leq [\sigma_{\text{bend}}], \quad (3)$$

where W_{bend} – resistance axial moment of a section for a rectangle.

$$W_{\text{bend}} = \frac{bh^2}{6}. \quad (4)$$

Let us express one of the projected parameters from dependence (4) (it is more convenient to express the width b):

$$b = \frac{6W_{\text{bend}}}{h^2}. \quad (5)$$

This expression is suitable for substitution in the previously proposed objective functions (1) and (2):

$$S = \frac{6W_{\text{bend}}}{h^2} h \rightarrow \min;$$

$$\frac{P}{2} = \frac{6W_{\text{bend}}}{h^2} + h \rightarrow \min.$$

To search for the minima of functions, it is necessary to equate their derivatives to zero; in this case it is advisable to take derivatives with respect to the variable h :

$$\frac{dS}{dh} = \frac{6W_{\text{bend}}}{h^2} = 0; \quad (6)$$

$$\frac{d(P/2)}{dh} = -2 \frac{6W_{\text{bend}}}{h^3} + 1 = 0. \quad (7)$$

Obviously, function (6) will tend to zero with increasing cross-sectional height, from which we can conclude that in order to reduce the metal consumption, it is necessary to take the height parameter h as large as possible.

Equation (7) has a solution:

$$h = \sqrt[3]{12 W_{\text{bend}}} = 0.$$

Then formula (5) takes the form

$$b = \frac{6W_{\text{bend}}}{\sqrt[3]{12^2 W_{\text{bend}}^2}}.$$

We find the aspect ratio of a rectangular cross section b/h :

$$\frac{b}{h} = \frac{6W_{\text{bend}}}{\sqrt[3]{12^2 W_{\text{bend}}^2} \cdot \sqrt[3]{12 W_{\text{bend}}}} = \frac{1}{2}.$$

Thus, the optimal ratio of the height h and width b of the rectangular cross-section of the rod, perceiving bending moments and transverse forces, is obtained.

We consider from this position a rectangular rod loaded with axial forces, for example, working in tension (the dependencies will be similar for compression). In this case, the limitation due to strength will take the form

$$\sigma_{\text{tens}} = \frac{N}{S} \leq [\sigma_{\text{tens}}],$$

where N – axial force in a dangerous section of the rod; $[\sigma_{\text{tens}}]$ – permissible tensile stress is determined by the selected material of the considered metal element.

The cross-sectional area S is expressed in terms of the projected parameters according to formula (1), from which, by analogy with the previous problem, the width b can be expressed:

$$b = \frac{S}{h}. \quad (8)$$

Substituting the obtained value in the objective function (2), we obtain:

$$\frac{P}{2} = \frac{S}{h} + h \rightarrow \min. \quad (9)$$

The derivative for function (9) with respect to h is equal to zero:

$$\frac{d(P/2)}{dh} = -\frac{S}{h^2} + 1 = 0.$$

This equation has the solution

$$h = \sqrt{S}.$$

Substituting the obtained value in (8), we obtain the expression

$$h = \frac{S}{\sqrt{S}} = \sqrt{S}.$$

Thus, the conclusion is obvious that in the presence of predominantly axial loading (when the rod is under tension or compression); the optimal cross-sectional shape of the metal structural element is a square.

Let us similarly consider a hollow rectangular section with the width and height of the outer sides B and H , respectively, with the width and height of the hole, respectively, b and h . The area of such a cross section for reasons of reducing metal consumption should strive to a minimum

$$S = BH - bh \rightarrow \min. \quad (10)$$

In the case of such a bending section, the restriction is described by formula (3). In this case, the resistance moment of the cross section is determined by the dependence

$$W_{x-x} = \frac{BH^3 - bh^3}{6H}; W_{\text{bend}} = \frac{BH^3 - bh^3}{6}. \quad (11)$$

The limitation on the condition of bending strength (11) and the objective function (10) make it possible to compose a system of two equations, however, four design parameters, and therefore unknown ones, are four. Thus, two more restrictions are necessary for the unique solution of the resulting system of equations.

To simplify operations with the mathematical model, we take an additional condition that allows us to obtain a fairly simple solution to the resulting system of equations. We consider the option when $H = B$ and $h = b$, i.e. the cross section is a square with a square hole.

Then dependences (10) and (11) take the form

$$S = B^2 - b^2 \rightarrow \min;$$

$$W_{\text{bend}} = \frac{B^4 - b^4}{6B}.$$

The analysis of the dependences shows that with positive values of the designed parameters, the area tends to zero with increasing values of B and b , the wall thickness decreases. The pattern extends to a hollow rectangular section with any aspect ratio. For obvious reasons, it is impossible to infinitely reduce the wall thickness and increase the parameters B and H . This will lead to an unreasonable increase in the dimensions of the metal structural elements on the one hand and the loss risk of local stability by the structural element on the other.

The extension to this situation of previous arguments about minimizing the area of the outer surface of a hollow rectangular rod, and, as a consequence, the perimeter of the cross section, leads to the obvious conclusion that the hole should be abandoned in favor of a solid section.

Results

The optimal parameters of metal structures are determined by a number of factors, among which the main ones are distinguished:

- the action direction of force factors;
- mass requirements for the metal structural elements;
- requirements for the dimensions of the metal construction elements.

Depending on the combination of these factors, the optimal cross-sectional shape of the rod may be different. Tables 1, 2 reflect the influence of the above factors on the shape of the metal structures of mining transport vehicles.

Depending on the nature of loading of the metal structure element and the requirements for it in terms of metal consumption, surface area and the presence of an internal cavity, the best cross-sectional shape is different. Moreover, depending on the priority and combination of these requirements, recommendations for choosing the best cross-sectional shape may be opposite.

In the case where the rod is predominantly loaded with axial forces, the presence of an internal cavity does not affect its mass, so the choice between a solid and a hollow cross section is based on structural considerations. If the metalwork is additionally required to minimize the external surface area, then

the square will be the optimal cross-sectional shape. The presence of an internal cavity for such a rod is undesirable. If there is a need to place any elements of the equipment inside the metal structure, then it is necessary to strive for the minimum dimensions of the cross section of the hole.

If the rod is loaded mainly with transverse forces and bending moments, and it is necessary to minimize the surface area of the metal structure, then it is advisable to refuse the cavity inside the rod. In this case, the height of the cross section should be twice its width. In the case where a cavity inside such a rod is necessary, it is preferable to arrange it so that the height h is as small as possible. This is due to the fact that the axial moment of resistance of a rectangular cross section decreases by an amount proportional to h^3 during the transition from a solid section to a hollow one.

In the presence of transversely directed loads from the point of view of minimum metal consumption, it is advisable to use a box section. If there is no restriction on surface area, then the width and height of the cross-section may be the maximum possible. In this case, the smallest wall thickness and weight of the metal structure are required. It is within such elements that it is preferable to have link transmission systems, hydraulic or electrical lines, sensors and other similar equipment.

There are several approaches to the selection of a criterion that determines the parameters of a hollow rectangular section. Firstly, it is possible to introduce a restriction on the minimum

permissible wall thickness, determined by the assortment of available products. Secondly, you can set the limit overall dimensions of the cross section, determined by the convenience of the layout of the metal structure. The third option is to use a comprehensive economic evaluation criterion that takes into account both the cost of the material from which the metal structure is made and the cost of coatings applied to its surface. The objective function in this case is the cost per length unit of metal:

$$C = C_m S + C_s P \rightarrow \min, \tag{12}$$

where C_m – cost of 1 m³ of rod material; C_s – the cost of coating per 1 m² of the rod surface.

In order to compare the cost of metal structures from various types of structural steel (carbon, low alloy and stainless), taking into account prices, high-quality square-rolled products are selected as an example. As a result, it was found that with the same axial load perceived by the rods, the cost of 1 m length of the metal structures made, respectively, of the steels St3, 09G2S and 12Kh18N10T, are in the ratio 1.8 : 1 : 3.7. The masses of rods of these steels are in the ratio of 1.9: 1: 0.7. Thus, the lowest cost of metal construction determined by formula (12) is achieved by using 09G2S steel. However, the least weight is the metalwork made of stainless steel, which, in addition, in some cases does not require the application of a protective coating.

Conclusions

The given recommendations allow us to reasonably choose the best cross-sectional shape of the metal elements of mining transport vehicles, depending on the direction of the

Table 1. Optimum cross-sectional shape parameters of solid rods under various conditions.
Таблица 1. Оптимальные параметры формы поперечного сечения сплошных стержней в различных условиях.

The direction of the forces perceived by the rod	Metal construction requirements	
	Minimum weight	Minimum surface area
Transverse forces	$h/b = \max$	$h/b = 2$
	The maximum value of the ratio is limited by design considerations	
Longitudinal forces	The ratio of height and width can be any and is determined by design considerations	$h/b = 1$

Table 2. Optimum parameters of cross-sectional shape of hollow rods under various conditions.
Таблица 2. Оптимальные параметры формы поперечного сечения полых стержней при различных условиях.

The direction of the forces perceived by the rod	Metal construction requirements	
	Minimum weight	Minimum surface area
Transverse forces	$H = \max$ $B = \max$	$H/B = 2$ $h/b = \min$ $h = \min$ $b = \min$
	Maximum values are limited by section dimensions and wall thickness	Minimum hole sizes are limited by the dimensions of the elements placed inside the metal structure
Longitudinal forces	The ratio of height and width can be any and is determined by design considerations	$H/B = 1$ $h = \min$ $b = \min$
		Minimum hole sizes are limited by the dimensions of the elements placed inside the metal structure

current loads. In addition, requirements for metal construction, such as minimum metal consumption and / or surface area, are taken into account. The approach to determining the parameters of a hollow rectangular section, described by the objective function (12), is the most justified for such structures and with a high degree of probability excludes the possibility of obtaining irrational parameters of metal construction elements. Thus, the obtained patterns allow us to determine the most suitable shape and size of the cross section for the elements that make up the metal structures of mining transport machines, taking into account the set of require-

ments for them. For rods working in tension or compression, the most rational is the square shape of the cross section. For bending elements, a rectangular section with a height / width ratio of two is best suited. These conclusions are drawn from considerations of the least metal consumption and the smallest surface area of the metal structure. Taking the proposed recommendations into account when designing the metal structures of mining transportation machines will allow us to obtain the lowest values of metal consumption, and, consequently, the cost of the machine with the required technical characteristics.

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Обоснование параметров элементов металлоконструкций горнотранспортных машин

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Аннотация

Актуальность работы обусловлена необходимостью снижения металлоемкости горнотранспортных машин при сохранении прочностных характеристик их металлоконструкций. Эффективным инструментом для поиска наилучшего варианта сочетания проектируемых параметров с точки зрения получения конструкции с требуемыми свойствами является теория оптимизации. Реализация принципов и подходов этой теории применительно к металлоконструкциям горнотранспортных машин позволяет добиться такого сочетания их геометрических характеристик, которое позволяет получить наименьшую массу и габариты.

Цель работы: разработка принципа получения математических зависимостей, позволяющих определять наиболее подходящую форму и размер поперечного сечения для элементов, составляющих металлоконструкции горнотранспортных машин, с учетом направления воспринимаемых каждым элементом нагрузок.

Методология исследования. Использован оптимизационный подход, включающий определение проектируемых параметров, формулировку целевой функции и ограничений, накладываемых на проектируемые параметры.

Результаты и их применение. Установлены факторы, влияющие на значение оптимальных параметров элементов металлоконструкций горнотранспортных машин. Для различных сочетаний направления воспринимаемой нагрузки и приоритетных требований к металлоконструкции обоснованы оптимальные параметры поперечного сечения. Полученные рекомендации могут быть применены при проектировании рам с минимальной массой или габаритами.

Выводы. Представленные рекомендации позволяют обоснованно выбрать наилучшую форму поперечного сечения элементов металлоконструкции горнотранспортных машин в зависимости от направления действующих нагрузок. Учитываются требования, предъявляемые к металлоконструкции, такие как минимальная металлоемкость и (или) площадь поверхности. Для стержней, работающих на растяжение или сжатие, наиболее рациональной является квадратная форма поперечного сечения. Для элементов, работающих на изгиб, наилучшим образом подходит прямоугольное сечение с соотношением высота/ширина, равным двум. Эти выводы получены из соображений наименьшей металлоемкости и наименьшей площади поверхности металлоконструкции. Учет предложенных рекомендаций при проектировании металлоконструкций горнотранспортных машин позволит получить наименьшие значения металлоемкости, а следовательно, стоимости машины с обеспечением требуемых технических характеристик.

Ключевые слова: горнотранспортные машины, проектирование, оптимизация, параметр, металлоконструкция, поперечное сечение, поверхность, целевая функция.

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