MINING MACHINERY, TRANSPORT, AND MECHANICAL ENGINEERING

Research article

https://doi.org/10.17073/2500-0632-2022-2-170-179

Justification of geometrical parameters of lining plates for a belt conveyor drive drum

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Abstract

Belt conveyors are widely used in mining industry in open-pit and underground mining for moving bulkload in horizontal and inclined directions to the sites of processing. In order to create the best conditions of frictional contact between a belt and a drum, various methods of drive drum lining are used. The main lining material is rubber of different grades, providing proper coefficient of friction of a belt with a drum (within the range of 0.6–0.62). A drive drum lining material must have high wear resistance, thermal resistance, mechanical strength, ability not to accumulate electric charges on the surface and not to generate dangerous concentrations of toxic components (for example, chlorine gases, carbon monoxide) when heated. The use of ceramic lining opens up great opportunities for increasing lining durability and useful life of high capacity heavy-duty conveyors. The paper presents the results of the study of stress-strain state of belt conveyor drive drum ceramic lining plates. We used *Solid Work Simulation* environment in the study on the basis of the accepted analytical model of plate-belt contact for drive drum with diameter D = 1250 mm, belt width L = 1000 mm, and the belt entering branch tension value S_e = 25400 daN with regard to the value, direction, and nature of the acting loads. On the basis of stress-strain analysis of alumina ceramics lining plates, the favorable geometrical parameters of the plate cleats (projections) and the required properties of lining material ensuring the proper load-carrying capacity at the contact with the belt rubber facing were found. It was established that a plate cleat diameter for heavy duty conditions should be not less than 4.5 mm and its end round R should be within the limits of 0.5–0.6 mm, and, in the base, 0.3–0.4 mm at a cleat height of 1.0–1.4 mm in order to prevent stress concentration in hazardous sections. It was also established that alumina ceramics bending strength must be no less than 350 MPa for effective functioning of rubber-ceramic lining. Simulation of a plate stress-strain state on exposure to alternating loads made it possible to identify characteristic areas with maximum stress concentration, which were foci of crack nucleation. Thus, it became possible to predict lining useful life.

Keywords

belt conveyor, drive drum, ceramic lining, geometrical parameters, working section shape, stress concentration, properties, useful life

For citation

Ziborova E. Yu., Mnatsakanyan V. U. Justification of geometrical parameters of lining plates for a belt conveyor drive drum. *Mining Science and Technology* (*Russia*). 2022;7(2):170–179. https://doi.org/10.17073/2500-0632-2022-2-170-179

ГОРНЫЕ МАШИНЫ, ТРАНСПОРТ И МАШИНОСТРОЕНИЕ

Научная статья

Обоснование геометрических параметров футеровочных пластин приводного барабана ленточного конвейера

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Аннотация

Ленточные конвейеры широко применяются в горной промышленности при открытой и подземной добыче полезных ископаемых для перемещения насыпных грузов в горизонтальном и наклонном направлениях до мест их переработки. Для создания наилучших условий фрикционного контакта ленты с барабаном применяют различные способы футеровки приводных барабанов. Основными футеровочными материалами служат резины различных марок, обеспечивающие должный коэффициент сцепления барабана с лентой, величина которого находится в пределах 0,6–0,62. Материал футеровки приводных барабанов должен

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иметь высокую износостойкость, термостойкость, механическую прочность, способность не накапливать на поверхности электрических зарядов и при нагреве не образовывать опасных концентраций ядовитых токсических составляющих, например, хлорные газы, окись углерода. Широкие возможности в направлении повышения долговечности футеровок и повышения ресурса тяжелонагруженных конвейеров большой мощности открывает применение керамических футеровок. В статье представлены результаты исследования напряженно-деформированного состояния керамических футеровочных пластин приводного барабана ленточного конвейера. Исследование проводилось с использованием среды *Solid Work Simulation* на основе принятой расчетной схемы контакта пластины с лентой для приводного барабана диаметром D = 1250 мм с шириной ленты L = 1000 мм и величиной натяжения набегающей ветви ленты $S_{нб}$ = 25400 даН с учетом величины, направления и характера действующих нагрузок. На основе анализа напряженно-деформированного состояния футеровочных пластин из алюмооксидной керамики выявлены благоприятные геометрические параметры выступов и требуемые свойства футеровочного материала, обеспечивающие им должную несущую способность при контакте с резиновой обкладкой ленты. Установлено, что диаметр выступов пластин для тяжелых условий эксплуатации должен составлять не менее 4,5 мм, при этом радиус скругления торцевой кромки R желательно выдерживать в пределах 0,5…0,6 мм, у основания – 0,3…0,4 мм при высоте выступа 1,0…1,4 мм, что предотвращает появление концентрации напряжений в опасных сечениях. Установлено, что для эффективной эксплуатации резинокерамических футеровок предел прочности при изгибе алюмооксидной керамики должен быть не менее 350 МПа. Симуляция напряженно-деформированного состояния пластины при воздействии на нее знакопеременных нагрузок позволила выявить характерные участки с максимальной концентрацией напряжений, являющиеся очагами зарождения трещин. Таким образом, появилась возможность прогнозировать ресурс футеровки.

Ключевые слова
ленточный конвейер, приводной барабан, керамическая футеровка, геометрические параметры, рабочий профиль, концентрация напряжений, свойства, ресурс

Для цитирования
Ziborova E. Yu., Mnatsakanyan V.U. Justification of geometrical parameters of lining plates for a belt conveyor drive drum. *Mining Science and Technology* (*Russia*). 2022;7(2):170–179. https://doi.org/10.17073/2500-0632-2022-2-170-179

Introduction

Belt conveyors are widely used in mining industry in open-pit and underground mining for moving bulkload in horizontal and inclined directions to the sites of processing. They belong to continuous transport machines and, as compared with other types of mining transport are characterized by high energy efficiency and productivity [1–3]. The basic trends in belt conveyor development both in Russia and abroad consist, first of all, in increase of their productivity and useful life at the expense of traction stabilization [4, 5], automation of conveyor lines[1], application of powerful drives [6], increasing the length and strength characteristics of the applied belts along with ensuring high level of reliability and durability of driving and guiding assemblies [7–12], increasing the conveyors energy efficiency [13] and transportation efficiency with the use of intermediate drives of various designs [14].

The main traction and at the same time load-carrying body of a belt conveyor is conveyor belt *2*, which moves along a closed circuit (Fig. 1). Drive drum *1* imparts motion to belt via friction gearing.

For providing the best conditions of belt-drum frictional contact, in practice, different ways of drive drums lining are widely used. The main lining material, as

[1] Automation of conveyor lines. URL: http://mydocx.ru/8-5102.html (Accessed date 25.01.2022)

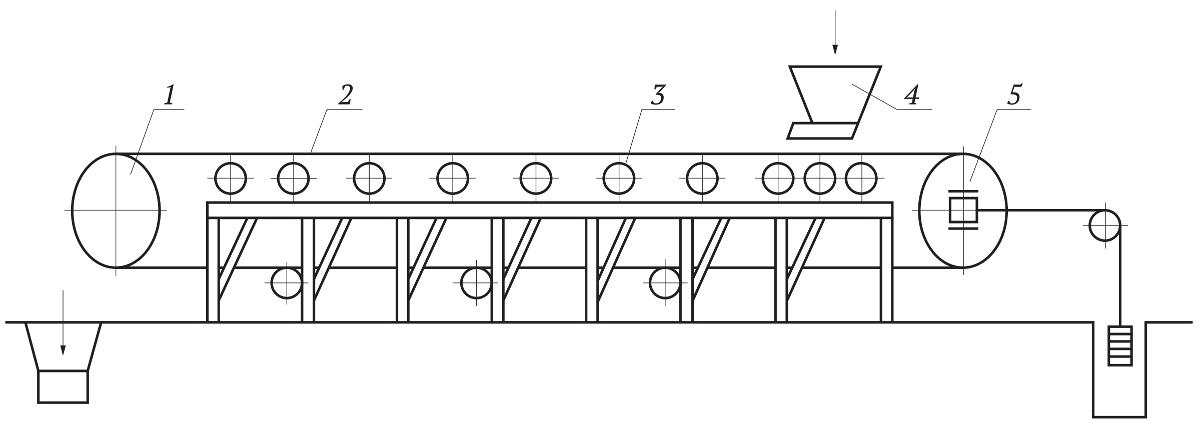


Fig. 1. Belt conveyor schematic:
1 – drive drum; *2* – belt; *3* – belt idlers; *4* – loading device; *5* – tension drum

a rule, is rubber of different grades (Fig. 2, *a*), which ensures proper value of the coefficient of friction between drum and belt (within the range of 0.6–0.62) [1, 8]. The rubber lining disadvantage is sharp decrease in the coefficient of friction in watery conditions. This leads to the belt slipping and loss of traction force.

A drive drum lining material must have high wear resistance, thermal resistance, mechanical strength, ability not to accumulate electric charges on the surface and not to generate dangerous concentrations of toxic components (for example, chlorine gases, carbon monoxide) when heated.

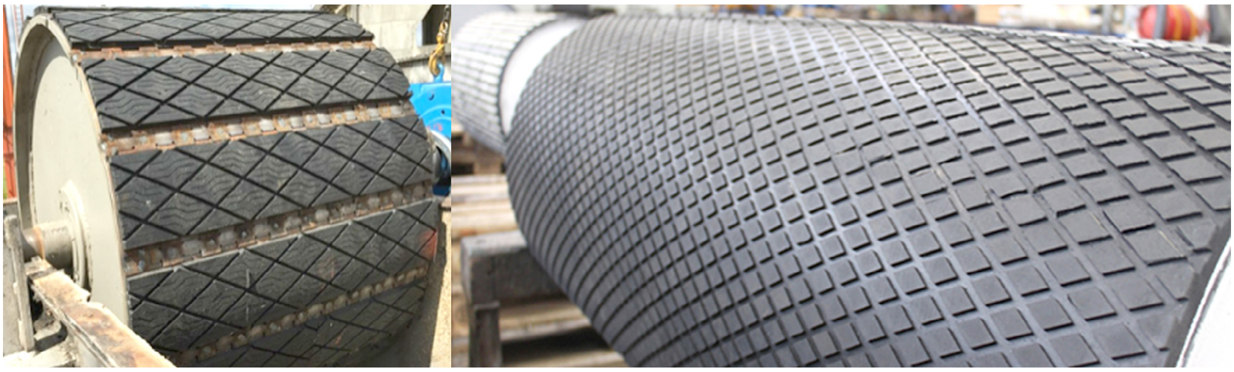
The use of ceramic linings opens up great opportunities for increasing the lining durability and useful life of high capacity heavy-duty conveyors (Fig. 2, *b*). Ceramic lining meets all of the above requirements. For the drums with diameter more than 800 mm, the composite two-three-layer rubber-ceramic, or metal-rubber-ceramic lining is used. Ceramic lining provides the best conditions of friction/friction with partial meshing drum-belt contact with the coefficient of friction of 0.8, which eliminates slippage even at excess moisture in the contact zone and significantly increases the productivity of conveyors, as well as securely fixes a moving belt on a drum width, preventing its slipping[2] [15].

[2] Ceramic plates for drum lining. URL: https://resursbelt.ru/catalog/effektivnost/futerovka/keramika-na-baraban/; Soloviev V. G., Soloviev S. V. Drive drum of a belt conveyor. Patent RU 81949 U1, 2009.

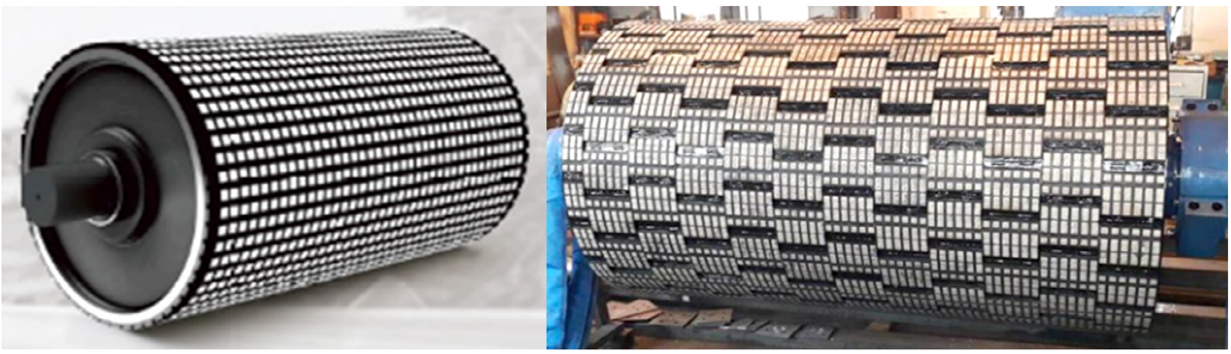
Research objectives and tasks

It is of great practical importance to reduce a belt slip along a drive drum and correspondingly reduce the wear of the belt and the drum surface. In this regard, ceramic lining is the most promising. However, despite their widespread application, there are still a number of urgent problems regarding to the need in increasing their useful life via creation of ceramic plates with a given geometry, improved mechanical and operational properties for the conditions of cyclic loading. Research literature presents recommendations on the selection of geometric parameters of highly elastic lining, while there are virtually no such data for rubber-ceramic lining. A number of leading foreign and Russian manufacturers of composite lining only report about dimensions and height parameters of ceramic plate cleats (projections), the values of which are determined mainly by technological considerations or operating experience[3]. At the same time achieving potential increase in a drive drum traction force and friction coefficient when using rubber ceramic lining first of all requires scientific substantiation of height parameters and shape of a bearing element, which is a cleat

[3] Ceramic plates for drum lining. URL: https://resursbelt.ru/catalog/effektivnost/futerovka/keramika-na-baraban/; T-REXCERA-REX 12x380x10000 rubber-ceramic drum lining. URL: https://centrobelt.ru/conveyor-maintenance/pulley-lagging/ceralag/cera-rex/



a



b

Fig. 2. Types of lining:
a – rubber; *b* – rubber-ceramic

immediately contacting with the belt and accepting the main load and providing the required friction during the drive drum rotation. The solution of these problems will allow determining rational parameters of the cleats, providing proper useful life of ceramic plates and, correspondingly, lining useful life along with increasing conveyors' operation and maintenance performance.

Techniques

When traction force is transmitted between a lining and a conveyor belt, the arising forces are described by the following relationship (Fig. 3, *a*):

$$\tau < fN, \quad (1)$$

where f is coefficient of friction between lining and belt; N is the normal force from belt pressure on drum, reduced to unit length ($N = S/R_d$, S is traction body tension force, R_d is drum radius).

In real operating conditions it is accepted to consider the arcs of relative slip (α_s) and relative rest (α_r) (Fig. 3, *b*) [12]. Friction force margin on a drum depends on the ratio of these arcs, while the reserve characterizes slip-free operation of a drive drum. At significant friction force margin (arc α_r) the elastic slippage of a belt relative to a drive drum decreases. As the friction force margin decreases, the slippage increases, and after reaching a certain limit (at $\alpha_s \cong \alpha_r$) the tractive resistance "disappears" and a belt begins to slip relative to a drum. Thus, the traction force is transmitted at the slipping arc, while the arc α_r acts as the traction force reserve. At the same time, as shown in [16, 17], when using elastic lining, some part of the traction force is also transferred at the arc of relative rest.

The influence of geometrical parameters and lining material properties, which ensure drive operation without relative slippage of a belt on a drum, is considered in [12, 16, 17]. In this case the shear of lining with the height H under the effect of distributed forces τ is expressed by the following relation: $\tau = G\gamma$, where G is shear modulus of lining material; γ is angular (shear) strain of lining (Fig. 3, *c*).

The increment of force S at section dx is defined by the equality, where it is assumed that $\gamma = u/H$:

$$dS = B\tau dx = \frac{G}{H}Budx. \quad (2)$$

After a number of transformations in studies [12, 16], traction factor on a lined drum, which carries out the traction force transfer without relative slipping, was expressed by the following formul:

$$\frac{S_e}{S_l} = chml \text{ or } \Phi = chml, \quad (3)$$

Taking

$$m^2 = \frac{G}{EHh},$$

after transformation we have got

$$\Phi = ch\sqrt{\frac{G}{EHh}}l, \quad (4)$$

where c is arbitrary constant, determined by boundary conditions; h is thickness of conveyor belt; l is the arc length of arc of belt contact; H is lining height; G is shear modulus of lining material; E is modulus of elongation.

After transformations, according to [16], the equation takes the form:

$$arch\frac{S_e}{S_l} = \sqrt{(G/H)(B/E_0)}l, \quad (5)$$

where $E_0 = EhB$ is belt longitudinal rigidity; B belt width; S_e and S_l is tension of entering and leaving branches of conveyor belt, respectively.

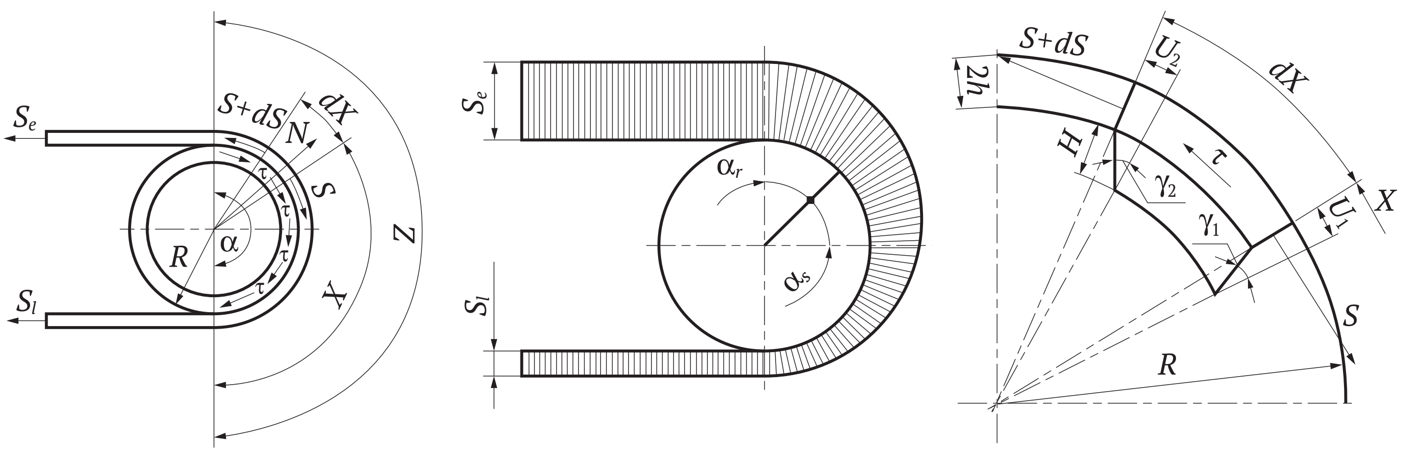


Fig. 3. Schematic of traction force transfer by a drum on:
a – non-weighted, non-stretchable thread; *b* – tensile thread without lining; *c* – tensile thread with lining

It follows from formulas (4) and (5) that, along with a belt material, the lining material rigidity and height parameters have a significant effect on the tractive force value.

The ultimate angular strain of a lining element (Fig. 3, *c*) is defined as:

$$\gamma_{lim} \cong tg\,\gamma_{lim} = \frac{u_0}{G}, \quad (6)$$

where u_0 is ultimate value of belt strain.

Study [17], devoted to research of highly elastic drum lining parameters, concluded that the increase in thickness of lining and especially its serrated part contributed to the increase of traction ability of a drive drum.

It should be noted that in a ceramic lining, a working element is a plate cleat, the height and diameter of which must be strictly regulated due to ceramics brittleness. Bearing capacity and operating characteristics of lining are first of all defined by stability and integrity of a cleat, therefore substantiation of its height parameters, shape (geometry), and required strength properties is an important applied research task, the solution of which will improve heavy-duty conveyors' performance and efficiency of drive drum lining maintenance and repair.

Cleats take up both by normal and circumferential forces while rotating drum and, consequently, their resistance to rupture determines bearing capacity of lining, especially in the cases when plates are fixed by glue directly on a drive drum shell without elastic rubber base.

As a rule, cleats are distributed over a plate surface at a certain distance from each other, often in chessboard order, which creates a kind of topography for implementation of contact with a belt on the principle of “friction with partial meshing”, as well as the possibility of removing water, dirt, and other mechanical particles from the contact zone of plates with the belt. At the same time, the plate-belt contact zones location in single areas of the plate working shape aggravates the loading of each individual element and requires the lining material to have high performance characteristics.

The limiting factors of ceramics application in friction assemblies of belt conveyors are the reduced crack resistance and fatigue strength (bending strength) of the material, caused by heterogeneity of applied ceramics structure, the presence of latent defects and porosity in it.

Increasing plate cleats height is expedient up to a certain value only in order to avoid their rupture under the action of cyclic operating loads.

The interaction of a conveyor belt with a lined drive drum is rather complex process that requires consideration of a large number of factors. The available mathematical apparatus used to identify the relationship between lining strains and circumferential forces is very difficult for engineering calculations, overloaded by a large number of coefficients and often does not allow to take into account all factors [17]. Therefore, computer modeling capabilities were used to solve the tasks.

Currently, in mining, geotechnics, and geophysics, methods of computer simulation and numerical analysis allowing fairly accurate description of various states of technical system elements are widely used to describe and study complex production processes occurring in various mining and geological conditions, as well as solve a number of applied problems in the field of mining machine drives, belt conveyors, and conveyor belts [18–25].

In order to identify favorable geometry of ceramic cleats (inserts), digital models of lining plates were created and the stress-strain state of plate cleats in contact with a belt was investigated taking into account the direction of the existing loads [17]. It was considered that a belt under the action of tangential forces experiences shear strain, and a lining experiences both shear strain in the circumferential direction and compression shear strain in the radial direction (Fig. 4), that is, it occurs in a complex stress-strain state (SSS).

The lining stress-strain state study assumptions were as follows:

– a ceramic lining material is isotropic;

– centrifugal forces are not taken into account;

– at the arc of belt contact with lined drum, Euler's law acts;

– in investigating lining stress-strain state, only steady-state processes are considered;

– shear strains of the elastic part of a lining, into which ceramics is embedded (vulcanized), are low enough and do not exceed 10% of its thickness;

– a belt is assumed to be absolutely elastic.

Computer simulation of the loading process was performed using *Solid Work Simulation* software for lining of drum with diameter D = 1250 mm, belt width L = 1000 mm, and the belt entering branch tension value S_e = 25400 daN. Alumina ceramics with compressive strength of 950 MPa, bending strength of 390–400 MPa, and modulus of elongation E = 374 ГПа. GPa were taken as a material for lining plates. Poisson's ratio ν was taken as 0.3. Shear modulus G was determined by the following formula:

$$G = \frac{E}{2(1+\nu)}.$$

When simulating the contact, the following constraints were taken into account [11]:

– maximum allowable belt tensions at the point of entry on a drum are 0.16–0.25 of the tensile strength of available belts of corresponding width;

– the load on a lining can be up to 1000 kN.

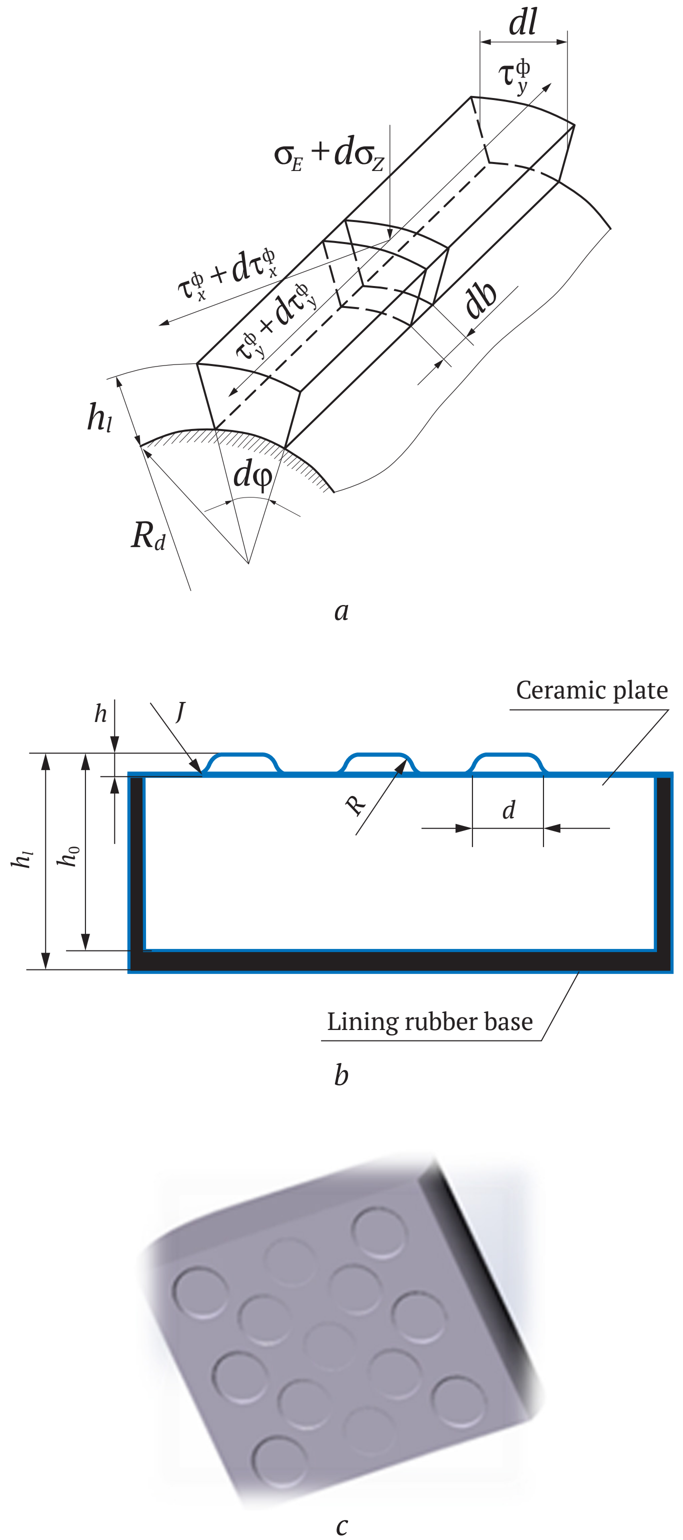


Fig. 4. Schematic diagram for analyzing stress state of elementary sections of a drum ceramic lining (*a*), parameters of ceramic insert (cleat) (*b*) and a digital model of the imprint of ceramic plate cleats in the rubber belt cover due to elastic contact (*c*):
R_d is radius of drive drum; h_l is total lining height; h_0 is ceramic plate height; σ_z – is normal stress; τ_x^ϕ, τ_y^ϕ are tangential stresses in the circumferential direction and across drum width, respectively; *d* and *h* are cleat diameter and height; *J* is radius at the base of a cleat; *R* is cleat end round (end bending radius)

A plate dimensions ($L \times B \times h_0$) were taken as 20×20×8 mm, a cleat diameter *d* varied in the range of 3.0–4.5 mm, a cleat height *h* varied from 1.0 to 2.0 mm, a cleat end round *R* ranged 0.2–0.8 mm, radius at the base of a cleat *r* ranged from 0.2 to 0.4 mm.

The imprint of the digital model working surface on a belt rubber cover, shown in Fig. 4, *b*, evidences that the greatest pressure is experienced by the plate peripheral cleats, which come into contact with the belt and leave the contact when the drum turns.

The maximum specific shear stress on the drum was determined by the following formula [17]:

$$\tau_{\max} = \frac{S_e}{B(R + h_l)}\mu,$$

where S_e is tension of conveyor's entering branch; *B* is belt width; *R* is radius of drive drum without lining; h_l is lining thickness; μ is coefficient of friction.

Findings

The findings of simulation of the stress-strain state of a ceramic plate are shown in Figs. 5, 6, and 7.

Fig. 5 shows solid digital models of the plates with characteristic zones of stress concentration in the most vulnerable points. Thus, the stresses are localized mainly at the base of the cleats (Fig. 5, a), as well as in the middle part of the lower base of the plate. During the operation of ceramic lining defects begin to nucleate exactly in these areas, thus limiting the plate's useful life at insufficient level of mechanical properties, in particular, bending strength. This property determines the fatigue strength of a ceramic plate and, correspondingly, the resistance to cyclic loads. It has been established that effective operation of rubber ceramic lining requires the (plate) alumina ceramics bending strength to be at least 350 MPa, whereas that of the ceramics used in recent lining is 280 MPa only.

At the first stage, the diameter and height parameters of the cleats were investigated. Fig. 6 shows a graph of stress dependency on the height of cleats under the most unfavorable contact conditions and loads at diameters 3.0 mm (curve 1), 3.5 mm (curve 2), 4.0 mm (curve 3), and 4.5 mm (curve 4). The graphs show that stresses increase with increasing the cleats height and reach a maximum at the height of 1.8 mm. The stresses are concentrated at the base of the cleats that leads subsequently to crack nucleation and accelerated failure of the cleats.

Curve 4 indicates a favorable stress field at the bases of cleats 4.5 mm in diameter due to larger cross-section and, consequently, better resistance to strain and cracking under cyclic loading conditions. The stresses simulation findings showed that the height of the cleats 3.0 mm in diameter should not exceed 1.2 mm. At the same time, the height of the cleats 4.5 mm in diameter can vary within the range of 1.0–1.8 mm.

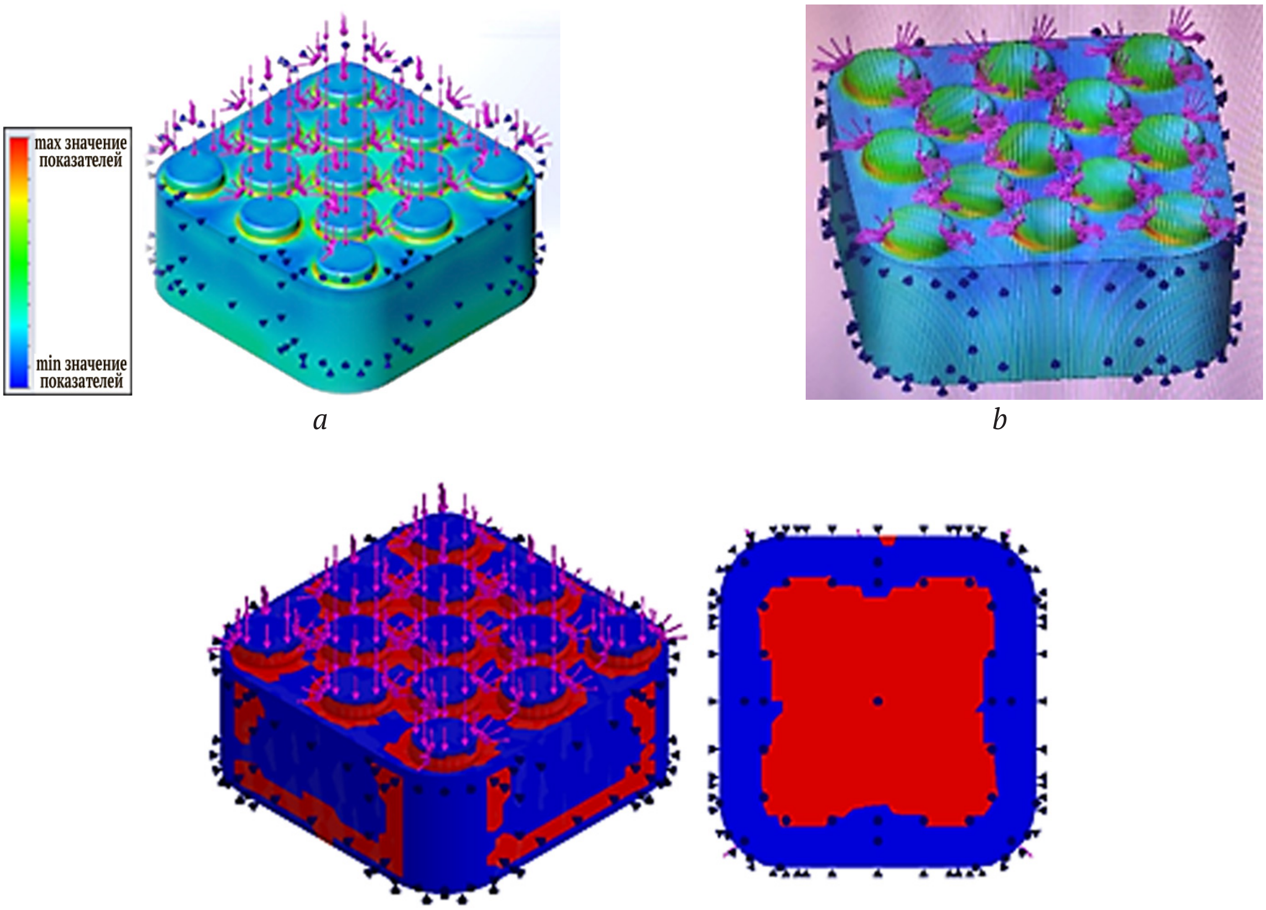


Fig. 5. Simulation of the stress-strain state of digital solid models:
a – when loading cleat 4.5 mm in diameter and 1.4 mm high with radius at the base *r* = 0,25 mm, end round *R* = 0,4 mm simultaneously by tangential and normal forces; *b* – when loading cleat 4.5 mm in diameter and 1.8 mm high by tangential force at *r* = 0,25 mm and *R* = 0,8 mm; *c* – simulation of stresses under cyclic loading of a plate (areas of fatigue crack nucleation at the cleat bases and in the central zone of the solid part of a plate are shown in red)

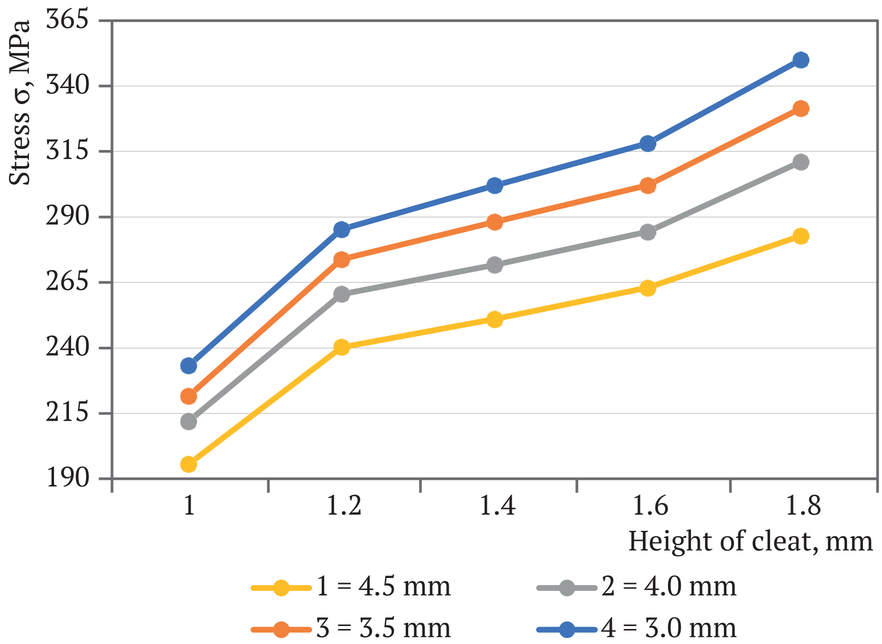


Fig. 6. Stress at plate cleat bases as a function of cleat height and diameter

Fig. 7 shows the results of a numerical experiment with the stresses obtained for various combinations of varied parameters such as a cleat height, round end *R*, and cleat base radius *r*. The analysis was performed for cleats of 4.5 mm in diameter.

The graphs show that significant increase of stresses is observed with decreasing the cleat base radius, and the greater the cleat height, the higher magnitude of the increase. For instance, decreasing *r* from 0.4 to 0.2 mm at *h* = 1.4 mm and *R* = 0.3 mm results in increasing stresses from 260 to 340 MPa. At the same time, changing end rounds R results in insignificant changing the near-end stresses.

The numerical experiment data allowed determining the most rational geometrical parameters, which provided favorable conditions for contact of plates with belt under extreme loading conditions. It can be seen from the graphs that the best contact conditions, in terms of the resulting stresses, occur at the following values of geometric parameters: *h* = 1.0–1.4 mm, *R* = 0.4–0.6 mm and *r* = 0.35–0.4 mm.

The research of strain-stress state of ceramic plates allowed producing their digital models (Fig. 8) that made it possible to produce their prototypes with different topography of working section for further experimental research. Fig. 7, *b* shows lining prototypes with ceramic plates embedded (vulcanized) into rubber substrate. The prototypes were made of different fine alumina ceramics grades, which have a dense structure and improved physical and mechanical properties. The plate test results will be presented in the next publications.

Simulation of the stressed state of a ceramic insert (plate) under cyclic load allowed determining the areas of fatigue cracks nucleation (Fig. 5, *c*). The Figure shows that the area of high stress concentration is observed at the cleat bases and in the central part of the lower plate plane. This is probably where fatigue cracks will begin to develop and eventually lead to plate failure.

Conclusion

1. On the basis of stress-strain state analysis of alumina ceramics lining plates, favorable geometrical parameters of cleats and the required properties of the lining material ensuring the proper bearing ca-

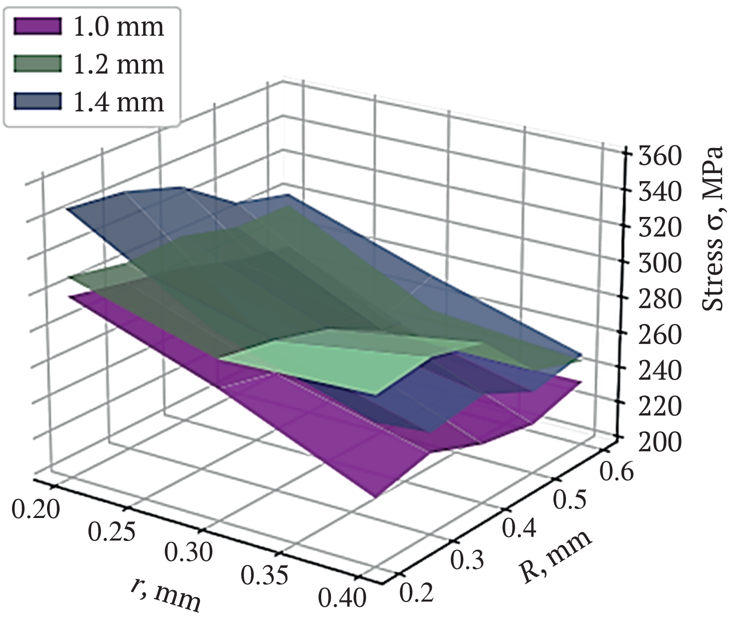


Fig. 7. Stress as a function of geometrical parameters of ceramic plate cleats: radius at the base *r* and end edge *R*

a *b*

Fig. 8. Digital models (*a*) and prototypes (*b*) of ceramic plates for rubber-ceramic lining

pacity at their contact with the belt rubber cover were found. It was established that a plate cleat diameter for heavy duty conditions should be not less than 4.5 mm and the end round R should be within the limits of 0.5–0.6 mm, and, at the base, 0.3–0.4 mm, at a cleat height of 1.0–1.4 mm to prevent stress concentration in hazardous sections.

2. It was also established that the alumina ceramics bending strength must be no less than 350 MPa for effective functioning of rubber-ceramic lining.

3. Simulation of a plate stress-strain state on exposure to alternating loads made it possible to identify characteristic areas with maximum stress concentration, which were foci of crack nucleation. Thus, it became possible to predict lining useful life.

4. Using the obtained digital models of lining plates, production prototypes were produced in the aim of conducting further in-situ tests of lining elements. The production prototypes were made using ultra-disperse alumina ceramics.

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Received 08.02.2022
Revised 14.05.2022
Accepted 30.05.2022