Research of the wear mechanism of the rubber lining mining trucks

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Abstract. The rubber lining used to protect the bodies of mining trucks is characterized by impact at an angle to the surface of the lining. Described experimental installation, allowing to model the impact of single solid particles at an angle to the surface of the rubber. It is established that the basis of the mechanism of the fracture of rubbers under oblique impact is cracking. The development direction of cracks is approximately equal to the angle of attack, i.e. the direction of the force of impact. The destruction is cyclical in nature and follows the scheme: the tear of the surface — rip crack — turn cracks and separation of the fragment. Factors determining the length and depth of the development of the initial crack set.

Keywords: elastomers, failure mechanism, failure evolution, solid particle impact at an angle to the surface

1. Introduction
The wear of materials by a flux of solid abrasive particles is characteristic for a large group of machines and equipment. Including lining of bodies of mining trucks. These wear modes are specific due to a complex of factors that affect the process of surface deterioration, including the dynamic (impact) character, local effect, dependence of the normal to tangential load ratio on the angle of attack, the small friction path or its absence, short-term contact, etc. [1, 2].

For certain operating conditions, the most effective way to reduce wear is considered the method of gumming [1]. To improve the wear resistance of rubber coatings, it is important to know how rubbers fail under the dynamic action. The investigations conducted today with these aims are still insufficient to formulate a generally accepted viewpoint on the wear mechanism and stages of the deterioration of elastomers in a flow of solid particles. To get answers on these important questions, it is proposed to subdivide the whole complex of phenomena observed during wear and the factors responsible for the failure behavior into simpler constituents and study failure regularities of rubbers by a single particle impact at an angle to the surface.

The most probable trajectory of cracking was determined in the course of investigations of the stress-strain state of the rubber surface layers. It follows from solving Flaman’s problem [4, 5] for an elastic half-space subjected to the force action at an angle to the surface [5] that the tensile stresses appear in the backside behind the sliding indenter. They look like a set of radial arcs that originate at the point of contact tangential to the force line. The crack is anticipated to arise perpendicular to the tensile stress; so far, it originates at 90° to the surface and adheres to the arc up to the zero line that separates the...
regions of compression and tension, thus forming an angle equal to that of the attack, i.e., to the angle of inclination of the force that affects the surface. A characteristic feature of rubbers is their low elasticity modulus, which results in considerable deformations under the shearing force. Therefore, the crack in the near-surface region that appeared at the strongest strain perpendicular to the surface would obtain a certain inclination upon the removal of the load. It follows that the crack is a result of the interference of two processes that occur simultaneously on the surface. This crack finally acquires a direction close to the angle of attack when a particle impacts the rubber surface.

2. Materials and methods
To verify the regularities established previously theoretically, the experimental investigations were fulfilled using a specially designed facility. This facility is able to model a single multiple repeated oblique impact of a solid particle against the elastomeric surface. Its parameters closely approach those of the real impact while providing the invariable position of the contact spot upon each impact.

The above problem is solved using an oscillating crank-and-slot lever mechanism with a rocking stone in the link. On one end of the link, there is an indenter that moves over a preset trajectory. By displacing the point where the stone is fixed on the link in vertical and horizontal directions, it is possible to impart a trajectory to the indenter that repeats the motion of the solid particle upon impacting the rubber surface at an angle in the range of 0° - 80°. This makes possible to keep to a physical similarity of the collision process in what concerns the relative motion mode of the indenter and the sample material in regard to the friction path length, time of penetration, impact force of the particle, and some other parameters.

A general scheme of the facility is shown in Fig. 1. The motor shaft has a fixed crank 1 that sets in motion link 2. The rocking stone 3 of the link serves as another fulcrum for the link able to turn round its axis in the plane of the facility. The adjusting screw mechanism 4 enables to shift the point of fixation of the stone in vertical direction while the screw mechanism 5 in the horizontal direction. This assists in setting the required trajectory of motion of indenter 6 in relation to rubber sample 7. The sample rests on a supplementary rubber spacer 8 and metallic disc supported by a spring 9. The spring is prestressed with the help of disc, screw 10, and a set of adjustable washers.

By displacing the rocking slider 3 vertically using the screw mechanism 4, the friction path l is set (Fig. 1b) and determined by the angle of attack α. The screw mechanism assists in setting the given angle of penetration α and of recoiling α (Fig. 1c).

It was established earlier[7] that it is peculiar for the relative motion of the particle and the surface material to shear together initially further followed by the particle sliding. The ratio of these phases of their motion depends on the angle of attack. When the angle of attack is small (0° to 30°—35°) the particle impact results in the elastic shear and relative sliding of the surfaces. In the case when the angle of attack is large (50°—90°), only the elastic shear occurs. In the interval of 35°—45°, there is a transient zone. The kinematics of the relative motion of a particle and the surface determines the surface failure mechanism on the contact spot as well. In this connection, the inves—tigations of the wear mechanism were...
conducted for three characteristic angles of attack, namely: 70°, 40°, and 20°. Angles 70° and 20° are the mean in their zone, while 40° represents the processes that occur on the transient boundary portions.

The present facility models an impact of a steel ball 4 mm in diameter, which means that the experiment involves strongly rounded abrasive particles.

The test rubbers were based on isoprene (I2 and I4) and butadiene styrene (C2 and C4) rubbers (Table 1). The physicomechanical properties were controlled by varying the filling degrees of the rubber used by technical carbon of grade P-514. The filling was 20% and 40%, correspondingly. The curing agent was sulfur. Index 2 for the rubbers means a lower modulus and resistance to tear but higher elasticity. The regularities of surface failure are little dependent on the rubber type. Their elastic and strength characteristics are of greater importance for the materials.

Table 1. Main physicomechanical properties

| Unit                  | I2   | I4   | C2   | C4   |
|-----------------------|------|------|------|------|
| Modulus at 300%, MPa  | 4.5  | 12.5 | 5    | 14.0 |
| Ultimate strength, MPa| 13   | 18.1 | 5.2  | 15.3 |
| Resistance to tear, KN/m| 37.0 | 37.3 | 16.1 | 36.3 |
| Shore hardness, A     | 50   | 70   | 48   | 68   |
| Elasticity, %          | 74   | 51   | 57   | 39   |

3. Results and discussion

Figure 2 presents the photos of the contact spots on the elastomer at the angles of attack 20°, 40°, and 70° for the state before breakage. The evolution of the contact spot wear on the rubber sample at different angles of attack shows no principal differences. The difference consists in the number, direction and depth of the cracks.

Figure 2. View of a contact spot at different angles of attack during the second stage of breakage (*8): (a) 70°; (b) 40°; (c) 20°.

The general schemes of the wear process were formulated based on the analysis of experimental data for different angles of attack (Fig. 3). The following three stages can be identified: run-in, onset and crack propagation, scoring, and the separation of the fractured rubber fragments.

Frayed patches initially appear and the surface changes its color. In the last third of the contact spot, a small abraded patch is formed. At the center at a slight shift in the direction of the velocity vector, a nonabraded projection appears like the one formed at the direct angle of attack. Afterwards, this projection is subjected to the mechanical destruction. The frayed patch surface is worn-out by the slippage of the indenter and rubber during sliding with formation of microscoring sites. These microscoring sites, which are about 0.01 - 0.05 mm in size, are shown in Fig. 4. This zone migrates from the center to the periphery of the contact spot and back as the indenter penetrates and exits the sample. The rubber with rather high elasticity modulus does not show very high flexibility (S < 40%). Therefore, at the initial stage, residual deformation arises in response to indentation.
Figure 3. Scheme of surface failure evolution modeled on a facility for impacting at the angles: (a) 70°; (b) 40°; (c) 20°.

Figure 4. Surface wear of the contact spot with microscore formation (x120).

When the impact energy is not large, the wear mechanism can stabilize during the first stage, so the amount of wear will depend mainly on the number of loading cycles.

During the second stage, the fatigue processes impair the surface layer strength. At a certain fatigue level the sample undergoes tear in response to the impact force, crack formation and propagation (Fig. 2). The surface cracks are arc wise with their ear directed towards the motion. This is because the deformation under the indenter center bears the highest tangential shear in contrast to its edges. The arc-form proves that cracking is initiated in the moment of the maximal shear of the surface by the friction forces. Upon the load removal, the rubber returns into its initial condition. This fact supports the hypothesis on the mechanism of cracking at tension of the surface layer. The angle of the crack onset is close to that of the attack [6], as is shown in Fig. 5 on the contact spot sections.

Figure 5. Effect of the angle of attack on crack propagation (x IQQ): (a) $\alpha = 70^\circ$; (b) $\alpha = 40^\circ$; (c) $\alpha = 20^\circ$.

During the third stage, the sample undergoes scoring and spalling accompanied by cracking. The process of scoring includes turn of the initial crack by 90° to the direction of its development, the scoring of the fragment, and its tear away (Fig. 6). As follows from Figs. 5 and 6, the wear fragments approach in their shape a triangular prism. The turn of the crack can be explained by two reasons. Firstly, the fatigue weakening of the surface layer with crack deepening is impeded thus producing insufficient energy for the further crack propagation. Besides, the crack approaches so-called zeroth vector that detaches the tensile stresses from the compressive ones [6]. The wear of the surface results in the formation of a specific undulated structure. In general, it resembles Shallamach’s picture.

The kinetics of the cracking and rate of transfer from one stage to another depends on the type of rubber, the physicomechanical properties of the rubbers, and the values of the angle of attack and impact energy.
Table 2 shows a general principal tendency to abruptly decrease (four times) of the number of cycles up to the formation of a crack with a decreasing angle of attack. However, different types of rubber have their own peculiarities.

Table 2. Effect of the angle of attack on the number of loading cycles on the surface up to its failure under an impact pressure of 1.7/2.4 MPa.

| Rubber code | Angle of attack 20° | Angle of attack 20° | Angle of attack 20° |
|-------------|---------------------|---------------------|---------------------|
| I2          | 150/110             | 500/300             | 2700/2600           |
| C2          | 200/120             | 400/350             | 3000/2800           |
| I4          | 1100/200            | 1600/1100           | 3100/2800           |
| C4          | 800/300             | 1800/1000           | 5300/4100           |

For instance, for the isoprene-based rubber I4 the time till crack origination is lasts longer at both angles 70° and 20°. Highly elastic rubbers I2 and C2 have a shorter run-in since the friction force is similar to I4 and C4 rubbers, while the rupture strength is 1.5 times less. One of the major factors that determine the rate of crack origination and the failure is the impact energy.

The table shows the effect of the impact energy on the incubation period, i.e., the initiation of rubber decomposition. The impact energy is expressed via the specific pressure. The stronger rubbers I4 and C4 are less dependent on the angle of attack and are more durable than the weaker rubbers. Weaker rubbers I2 and C2 show a low rupture strength and resistance to tear, their impact energy at small angles of attack only slightly affects their durability. At larger angles of attack their durability is comparable to that of stronger materials. This can be attributed to the effect of fatigue properties in addition to the strength ones. The fatigue properties are closely connected with the value of mechanical losses, i.e., with elasticity, which is about 60% for C2 and I2 rubbers.

The wear rate depends not only on the crack formation velocity, but also on that of fragmentation of the worn-out surface layer. The larger the inclination angle of the crack, the more favorable the conditions created for scoring.

Figure 7 illustrates the dependence of the crack depth on the load and physicomechanical properties. For the present investigations, the impact force corresponded to the energy of a 4 mm in diameter steel ball moving at a velocity of 7, 11, 15, and 19 m/s.

The defining effect at 20° is exerted by the friction force, while the fatigue properties are more important at 70°, so the curve can be seen to be flattened. The deepest cracks are characteristic for 70° angles of attack and the most shallow cracks are formed at 20°. Nevertheless, the weaker rubbers, I2 and C2, have the same crack depth at 20° and 70°. It should be noted that
the scoring of the cracks begins at very similar depth values of cracking for all angles. For an angle of inclination of the crack of 20°, we have 0.25 - 0.40 mm, correspondingly, for both stronger and weaker rubbers.

If to estimate the crack depth $h_{cr}$ in fractions to the penetration depth $h$, it follows that for the weak rubbers ($c_r < 12$ MPa) $h_{cr}/h = 0.15 - 0.20$, and for the stronger rubbers ($c_r < 12$ MPa) is $h_{cr}/h = 0.10 - 0.12$. Consequently, the worn layer thickness makes up on an average of 0.1 - 0.2 of the penetration depth of the impacting particle.

There are investigations in corresponding scientific literature supporting the idea that the principle of cracking lies in the base of the wear mechanism of elastomers [7].

4. Conclusions

Present studies of the failure of the rubber surface by particle impacts at an angle to the surface have led to the following conclusions.

(1) Crack formation on the surface of the contact spot is the cause of elastomer fracture. In the case when the loads are not large, the micro- and submicrocracks are generated, which are by one to two orders less.

(2) It has been experimentally established that the angle of crack propagation relative to the surface coincides with the angle of the indenter action on the surface.

(3) The experiments have shown that with a decreasing angle of attack durability of the rubbers drops abruptly. At small angles of attack, rubbers with high-strength characteristics are the most durable. When the angle of attack is large, rubbers with higher elastic and fatigue properties (resistance to crack generation and propagation) turn out to be the most durable.

(4) The cracks are deeper at larger angles of attack, although the surface breakage rate is greater at smaller angles of attack.

(5) Scoring and the tear of the material begins as the crack reaches a certain length and depth depending on the physicomechanical characteristics of the rubber, as well as the values of the specific load and angle of attack.

(6) The wear mechanism of rubbers takes place in three main stages, namely, crack formation, propagation in depth, and the scoring and tearing of the rubber. The impact-induced wear mechanism of the studied rubbers at an angle to the surface can be defined as scoring.

The above-mentioned results may serve the base for the further development of wear-resistant formulas of rubbers that proceed from the established main causes of fracture in the interrelation with the physico - mechanical properties of rubbers.

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