Model of forming vibration mechanochemical solid lubrication coating on surface of steel rope

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Abstract. The paper presents materials on forming a vibration mechanochemical solid lubricant coating based on molybdenum disulfide on the surface of a steel rope during its production. A model of the formation of the surface layer is formed. A unit for applying a solid lubricant coating to a steel rope was developed and designed.

1. Introduction

In modern engineering industries, machines using rope traction are used to perform complex, essential and high-tech tasks. It is characteristic for such machines that a steel rope is an important, essential and expensive element. During operation, the steel rope is in direct contact with rollers, pulleys, drums and other mechanical parts of machines. In the process of studying the physical and mechanical properties of the rope, the authors noted that when the steel cord bends around a pulley (drum), the strands move relative to each other. In view of the structural features of the steel rope, namely in the places of its connection, in the docking locks (nodes), the strands are in a rigidly fixed state, a point of linear contact of metal to metal is formed in the friction pair “strand-core-strand”, which during the operation of the steel rope progresses to abrasion of the wires with their subsequent breaks.

The authors found that due to the lack of lubricants at the point of contact, the wires do not have sufficient mobility for normal operation of the steel rope, resulting in the effect of biting the strands, and their subsequent premature wear and failure.

To solve the identified problem, it is proposed to apply a vibration mechanochemical coating to the surface of strands wires of the steel ropes during the rope twisting. An analysis of domestic and foreign experience in the applying rope lubricants showed that in the manufacture and subsequent operation of a steel rope, grease lubricants are used [1-13]. The lubricants used do not meet up to date operational requirements: the lubricant cracks and dries during operation in the negative temperature range and is subject to runoff (sliding) during operation in the positive range. The method of applying lubricants does not contribute to proper adhesion on the surface of strands wires of a steel rope. The special methods for testing rope lubricants developed in recent years have made it possible to define that the currently used lubricants do not meet all the requirements for them.

Solid lubricants based on MoS₂ molybdenum disulfide [3-6] will be the most advantageous in terms of their operational properties and economic costs. This type of lubricant has good adhesion, cannot be removed during operation, penetrates the center of the rope and strands, and has the ability to cover the surface of the rope with a thin layer and harden quickly, do not evaporate and do not harden over time, do not contain alkalies, acids and other elements that cause corrosion.
The method of determining the nature of the location, size, depth and shape of traces was the basis for studying the mechanism of forming the vibrating mechanochemical solid lubricant coatings. Vibrating mechanochemical solid lubricant coating is applied through a layer of MoS$_2$ powder located in the contact area between the metal surface and the working medium. Adhesion occurs under the influence of surface forces, and the adhesion force is a function of the thickness of the gap between the contacting bodies. The essence of the method is that as a result of the vibro-wave interaction of the working medium and the part a relatively uniform layer of a plastically deformed active metal with a coating is formed at the surface. The initial contact of the particles of the working medium coated with MoS$_2$ occurs at the vertices of the metal surface microroughness. Areas covered with MoS$_2$ are formed at the points of contact. During further processing, the powder fills the microroughness troughs, first forming a loose layer, which subsequently compacts, and a uniform coating is obtained on the surface. Particles of molybdenum disulfide do not have a specific orientation, but in the contact area, they are oriented by the base planes in parallel to the surface being machined. This orientation of the particles determines the increased antifriction properties of the surface, extending respectively the steel rope operational properties during sliding friction.

The crystalline lattice of solid lubricants has a layered structure. The atoms of each layer are interconnected by strong chemical bonds, particular layers are interconnected by weak molecular forces, which ensures ease of sliding along the cleavage plane. The thickness of one elementary layer of MoS$_2$ is 6.25 Å. A molybdenum disulfide film with a thickness of 0.025 μm consists of 40 layers with 38 slip planes between them. High adhesion of molybdenum disulfide to metals is due to strong molecular bonds formed by sulfur atoms with the metal; the structure of the crystal lattice ensures the presence of high adhesive properties important for lubricants. Molybdenum disulfide has a hexagonal layered lattice in the form of a prismatic hexagon (Figure 1.).

*Figure 1.* Molybdenum disulfide crystal lattice.
The analysis shows that the most technologically advanced method of applying a solid lubricant coating is vibrational, rather than applying it with a brush, it is able to provide:
1) low coefficient of friction, increased adhesive ability of MoS$_2$ due to high contact loads;
2) crushing, uniform spreading down of molybdenum disulfide on the surface of the part.

In case of vibro-microwave exposure, particles of the working medium striking the working surface provide rapprochement of the metal surface in the contact area and the applied coating until molecular interaction forces occur [9, 10, 12, 13].

The intensity of interaction is affected not only by the contact of the powder with the surface being treated, but also by the processes occurring in the area of direct contact. Under the influence of normal and tangential forces, the surface layer of the metal is deformed due to the action of balls.

As a result of the circulation of the working medium and parts, a relatively uniform layer of plastically deformed active metal is shaped [5].

2. Materials and methods
Figure 2 shows an image of a brush applied molybdenum disulfide coating. This method is widely used in engineering and aircraft manufacturing for parts included in friction pairs. When analyzing the image of a surface coated with molybdenum disulfide (Figure 3), the disadvantages of this method become evident:
- molybdenum disulfide plates rise above the surface of the coating, therefore, the effort exerted by the brush is not enough to form a compacted uniform coating;
- molybdenum disulfide is not crushed, and, therefore, its intrusion into the micro / nano profile of the metal surface is impossible. In this regard the adhesive ability of the coating and as a result durability are reduced [7].

Figure 2. Surface morphology of ViMSLC molybdenum disulfide with different resolutions at the micro / nanoscale level: a - 1 micron; b - 200 nm; c - 400 nm.

Figure 3. Surface morphology of MoS$_2$ film applied by brush, scale 10 μm.
Analyzing the results of comparative tests, it can be concluded that when coating with a brush, that is, without applying a load, the crystallites of the MoS\textsubscript{2} powder have a disordered orientation and some molybdenum disulfide plates occupy a vertical position, and after running-in, they are oriented parallel to the slipping plane.

The MoS\textsubscript{2} film deposited in various ways has a high friction coefficient in the initial slipping period, which decreases and stabilizes after a certain period of time [8].

The results of determining the friction coefficient of the coating showed that the minimum friction torque is being set in the initial period of operation, that is, there is practically no running-in period. The running-in of the coating, the shaping of a film with good antifriction properties, are carried out directly in the coating process.

![Diagram](image)

**Figure 4.** Diagram of the model of forming vibration mechanochemical coating based on molybdenum disulfide.

3. **Results**

Based on the studies, the following model of the formation of vibration mechanochemical coatings based on molybdenum disulfide is proposed (Figure 4):

1. Mechanical contact and adsorption of MoS\textsubscript{2} particles at the time of external loading, due to the force of the collision of the ball with the surface of the processed material, elastic, plastic and elastoplastic deformation occurs in the contact area. Due to the convergence of the applied coating with the part, particles are adsorbed on the metal surface (Figure 4, a).

2. Activation of the surface layer of metal. Surface activation is carried out as a result of plastic deformation and an increase in the density of dislocations, the destruction of oxide films and the formation of surface areas, also an increase in surface area (Figure 4, a).

3. Formation of the boundary layer. This stage is carried out due to the crushing of MoS\textsubscript{2} crystals, their destruction of oxide films in the microrelief depressions, an intrusion of powder particles and their adsorption to the surface layer of the activating metal (Figure 4, b).
4. Formation of a lubricant layer. This stage is characterized by thickening of the particles of the deposited coating, grinding of crystals, their adhesion to each other, and shaping of a continuous layer of lubricant (Figure 4, c).

5. Formation of the surface layer of coating. As a result of sliding of the working medium particles relative to the formed surface, the powder particles are oriented by their base planes parallel to the friction surface (Figure 4, c).

As a result of the studies, it was found that the layer of solid lubricant of molybdenum disulfide formed during vibration processing is covered with a thin film having the orientation of the particles by their base planes parallel to the friction surface (see Figure 2.) Such a structure of the film, as shown by analysis, makes it possible to include nanoscale structures in it [6].

Figure 5. General scheme of utility model for applying a solid lubricant coating to steel rope surface while twisting.

Figure 5 shows the general scheme of a utility model for applying a solid lubricant coating to the surface of a steel rope during its twisting is presented. The utility model contains a working chamber (rectangular type) 1, rigidly fixed with springs 5 on the base 4, driven by a vibration motor 3. At the ends of the working chamber, a receiving and an output cover 6 are installed.
The utility model works as follows:
A working medium containing steel balls of various diameters and molybdenum disulfide powder are poured into the working chamber 1, and the facility is switched on for 1 hour. During this time, thorough mixing and grinding of the powder take place, as a result of which, all balls are covered with a continuous layer of lubricant. A working medium prepared in that way can be reused. Periodically, MoS$_2$ is added to the working chamber, the required amount of which is determined by the flow rate of the powder going to cover the workpieces. After adding the powder, the working chamber is also recommended to be switched on for 1 hour without parts for thorough mixing of the added powder. Steel wire 8 is passed through the working chamber through the receiving and output covers, and fixed on the tensioning devices of the rope machine 2. In order to prevent powder from spilling from the working chamber 1, rubber-metal cuffs are installed in the receiving and output covers 6. After the vibration motor 3 is turned on, the working medium moves, making two types of movements - oscillation and slow rotation of the entire mass. Steel balls move in concentric circles around the axis of the container (the "rolling" movement), "Rolling" balls across the entire inner surface of the container provides uniform surface treatment. The processed wire, passing through a vibrating machine, enters the rope machine 2, where the twisting process takes place. To avoid weaving of steel wires, during operation of the vibrating machine, the receiving and output covers are used, which rotate (slide) regardless of the vibrations of the working chamber. The duration and frequency response of the vibrating machine are selected depending on the operating conditions of the rope machine.

The technology proposed by the authors for applying an antifriction powder coating (MoS$_2$) on the surface of a steel rope and fixing it on a complex rope surface using local hardening and vibration processing opens up unique opportunities for obtaining a new level of coating properties: high strength, hardness, wear resistance, corrosion resistance, and sufficiently high ductility, while maintaining the high performance properties of the steel rope. The combined technique of surface treatment of steel rope allowed to extend the service life and to avoid the effect of abrasion of the strands relative to each other by sliding along the contact plane. The studies were carried out using a SUPRA25 electron microscope, which makes it possible to study the metal surface, coating material, continuously monitor the process, electron beam lithography, analyze failures and observe materials with ultrafine grain sizes (nm), analysis of inclusions in alloys and steels, analysis of fractures or development of new materials (Figure 6). The obtained results open the way for further studies of the possibility of introducing micro / nanomaterials and carbon nanotubes into coatings.

Figure 6. Surface microrelief of rope strand coated with MoS$_2$. 
Powder antifriction material, due to its layered structure, allows the mobility of the strand by sliding the nanoparticles of the powder and good adhesion resistance to the metal strands in the friction pair “core-strand-strand”, the layers of the powder antifriction material are displaced, which eliminates the possibility of a “biting” effect. To ensure mobility of the strand, the powder antifriction material fills the surface of the strand wire and interstring cavities, which allows the strands of the outer layer to move in the longitudinal plane and around its axis when bending the rope on the pulley (drum), distributing the uniformly resultant load throughout the rope and minimizing wear from abrasion.

4. Discussion
The application of a lubricant coating of MoS$_2$ leads to a significant decrease in the coefficient of friction. The wear resistance of the coated sample increases by 17 times. Molybdenum disulfide creates an additional lubricant layer under shock loads, thereby preventing a high degree of metal wear and providing effective protection. A utility model for applying lubricating coatings to a steel rope allows combining the operation of a rope machine and a vibrating machine without work conflicts between them. The thickness of the obtained vibratory mechanochemical solid lubricant coating is 3 to 5 microns. The rope lubrication begins already at the wire stage, and the application method allows strengthening and increasing the adhesive properties of the surface of the steel rope [3-6]. This reduces the processing time due to the continuity of the process and preliminary grinding of the powder. The introduction of this technique allows to increase the service life and reliability of the steel rope by 15%, as well as increase productivity and environmental friendliness of production by 10%.

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