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# Study of Wear Resistance of Antifriction Materials for Bushings of Lever-Hinge Mechanism of Lifting Installation Brake System

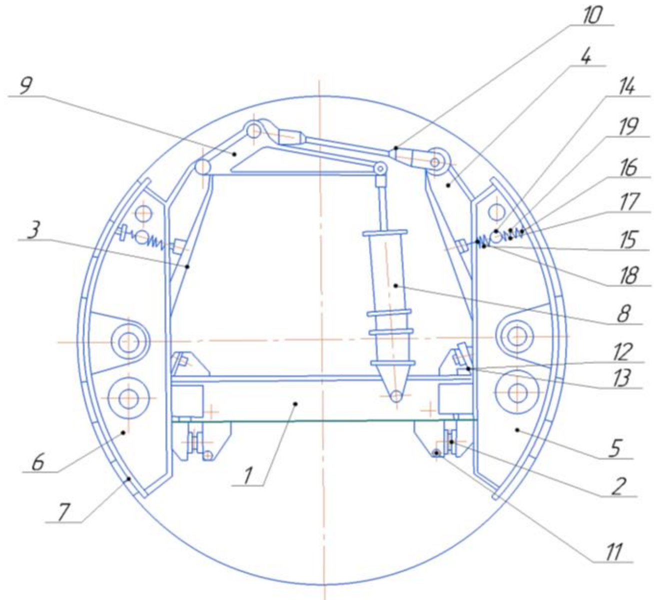
**Nurzhanova O.A.[1], Boyko S.B.[2], Berg A.A.[*1], Mukhitova A.E.[1]**
[1] Ablykas Saginov Karaganda Technical University, Karaganda, Kazakhstan
[2]Science technology centre Vostoktechnoservis LLP, Ust-Kamenogorsk, Kazakhstan
*corresponding author

**Abstract.** This article examines the pressing scientific and practical challenge of improving the operational reliability and wear resistance of friction units in lever-hinge mechanisms (LHM) of mine hoist braking systems. The authors provide a detailed analysis of the kinematics and operating characteristics of pin-sleeve friction units using equipment operated at the Kamyshinskaya and Artemyevskaya mines as an example. It is demonstrated that severe operating conditions - high radial loads (80 ÷ 150 kN), alternating pulses, constant vibration, and the presence of abrasive dust - lead to the degradation of protective oxide films, fretting corrosion, and an avalanche-like increase in radial clearances in the hinges. Bushing wear triggers dangerous edge pressures, fatigue stresses in the pin body, and a sharp drop in the mechanical efficiency of the drive. To address this issue, comprehensive comparative tribological tests of various antifriction materials were conducted using a ball-on-disk design on a Microtest automated tribometer under strictly controlled laboratory conditions. The experiments provided a detailed study of the patterns of change in the mass of mating bodies, the dynamics of the friction coefficient over a distance of 100 m, and the geometric parameters of the resulting wear craters for SCh-15 gray cast iron, traditional bronze, grade 45 steel with a $MoS_2$ solid lubricant coating, and ZhGr3M porous iron-graphite with molybdenum. The quantitative data obtained and the resulting graphical dependencies allow for a scientifically substantiated choice of material for upgrading friction units and transitioning to maintenance-free hinges.

**Keywords:** friction coefficient, wear time, tribological testing, antifriction materials.

**Introducrion.**

The articulated lever mechanism of a hoisting system acts as a power transformer, converting the energy of a pneumatic, hydraulic, or spring drive into normal pressure on the rim of the brake pulley [1,2]. The efficiency of force transmission in such systems is critically dependent on the kinematic design: even a 2–3% deviation in the lever geometry results in a significant drop in braking torque [3]. The articulated lever mechanism of a hoisting system brake used at the Kamyshinskaya, Artemyevskaya, and Artemyevskogo mines is shown in Figure 1.




1 - frame; 2 - hinges; 3, 4 - vertical levers; 5, 6 - brake beams; 7 - friction linings; 8 - brake drive; 9 - lever; 10 - rod; 11 - fixing screws; 12 - bracket; 13 - stop screw; 14, 15 - springs; 16 - rod; 17, 18 - bushings; 19 - nuts

**Fig. 1.** - Lever-hinge mechanism of the lifting unit braking system

The articulated lever mechanism of a hoisting system brake comprises a frame (1), a system of vertical levers (3, 4), brake beams (5, 6) with friction linings (7), and an actuator (8). Braking force is transmitted through a network of hinges (2) and rods (9, 10, 16). During braking, the drive (8) generates a force that is transmitted to the vertical levers via the lever (9) and rod (10). The key element at the pivot points is the connection between the bushing (17, 18) and the pin.

The pin performs a small-radius, reciprocating rotational motion relative to the stationary bushing, pressed into the eye [4]. A radial force F (80-150 kN) is applied perpendicular to the pin axis, causing contact pressure on the inner surface of the bushing. The specific operation of a hoist brake requires frequent starts and stops, which precludes hydrodynamic lubrication. The unit operates under boundary friction conditions.

Bushing wear is the dominant factor determining the reliability of the entire braking system [5]. The bushing, like a friction bearing, operates under oscillatory motion with small rotation angles and high specific pressures, reaching 30-50 MPa. In such conditions, hydrodynamic lubrication is impossible, and the unit operates in boundary friction mode [6]. This leads to gradual compaction of micro-irregularities and adhesive wear of the metal, which is visually manifested as an increase in radial clearance [7]. Even minimal wear of 0.5 mm on one lever arm, passing through the gear ratio system, can translate into an increase in the actuator rod stroke by several centimeters, reducing brake response.

The main physical and chemical problem is fretting corrosion in the pin-bushing assembly [8]. Due to alternating loads and micro-movements caused by vibrations from the operating machine, the protective oxide films on the metal surface are constantly destroyed [9]. The resulting wear products (iron oxides) are highly hard and act as an abrasive, accelerating the degradation of the assembly. In mine hoisting conditions, where coal or rock dust is present in the air, this process occurs in an avalanche-like manner [10]. If the bushing is not sufficiently hard relative to the pin, it fractures, creating an oval-shaped hole, which introduces an irreparable kinematic error in the braking force distribution.

The choice of bushing material determines the overhaul interval for the entire system. The traditional use of bronze (OCS 5-5-5 or BrAZh 9-4) is justified by their antifriction properties; however, under shock loads during emergency braking, they are subject to plastic deformation [11]. This installation uses PA-ZhGr3 iron-graphite (GOST 26802-86).

Geometric distortion of the hinge axis due to bushing wear causes edge pressure. When the bushing wears unevenly, the load is no longer distributed along the entire contact length, concentrating on the ends [12]. This creates a bending moment on the pin, which is not included in the static strength calculations. As a result, fatigue stresses accumulate in the pin body, which can lead to sudden brittle failure [13].

The problem of metal seizure or cold welding in the friction pair occurs when the lifting machine is idle for a long time under load (for example, on a stopper) [14]. Under high pressure, the oil film is squeezed out, causing direct contact between the juvenile surfaces. When attempting to release the brake, metal particles are torn from the bushing surface. To prevent this phenomenon, the application of solid lubricant coatings (molybdenum disulfide) is being introduced into modern design practice. These coatings create a separating layer at the molecular level, ensuring a smooth start-up of the mechanism even after several days of inactivity [15].

The effect of joint clearances on the system's dynamics manifests itself in the generation of shock pulses when the brake is applied [16]. When the drive begins to move, it first eliminates all the play in the worn bushings and only then begins to deform the brake pads. This impact on the lever chain creates peak stresses that are several times higher than the nominal ones. From the perspective of machine theory, wear transforms a rigid kinematic chain into a system with a variable structure and clearances, which is extremely difficult to accurately describe mathematically and can lead to unpredictable system behavior during automatic braking control.

Another important aspect is the method of securing the bushing in the lever body. A traditional press-fitted system can loosen under significant wear and heat, causing the bushing to rotate in its socket [17]. This is a catastrophic failure, as it begins to wear out the lever itself - an expensive cast or forged component.

Ultimately, combating bushing wear in a brake control system (RCS) means maintaining a consistent brake drive efficiency. A well-maintained system with minimal clearances has a mechanical $\eta \approx 0.92$-$0.95$, while a worn system loses up to 30% of the drive energy to overcome friction and deformation in the hinges. Modern trends are leading to the development of maintenance-free hinges, where the use of innovative polymers, coatings, and high-precision casting allows the brake system to operate for the entire service life of the machine without bushing replacement, setting the standard for reliability in mining [18].

An additional operational challenge is cold welding or solid-state seizure within the friction pair, which typically occurs during prolonged periods of machine inactivity while remaining under load (e.g., when a hoist is held stationary on a stopper) [19]. Under sustained high contact pressure, the residual boundary lubricant film is completely squeezed out, forcing direct contact between juvenile, chemically active metallic surfaces. Upon subsequent brake release, massive cohesive tearing occurs, stripping material clusters from the bushing surface. While the traditional deployment of copper-based alloys, such as traditional bronze (e.g., OCS 5-5-5 or BrAZh 9-4), provided adequate baseline antifriction performance, these materials exhibit high susceptibility to permanent plastic deformation when subjected to intense dynamic shock pulses during sudden emergency braking. Conversely, standard porous iron-graphite formulations like PA-ZhGr3 often lack the necessary shear strength and chemical stability to withstand the combination of fretting and abrasive dust infiltration over extended lifecycles.

From the perspective of advanced machine theory, heavy tribological wear fundamentally transitions what was designed as a rigid, predictable kinematic chain into a stochastic system with a variable structure and fluctuating clearances [20]. Such systems are exceptionally difficult to model mathematically, introducing unpredictable dynamic behavior and destabilizing the feedback loops required for automated, high-precision braking control. Additionally, traditional press-fitted bushings frequently suffer from thermal-mechanical loosening due to frictional heating and wear, leading to the catastrophic rotation of the bushing within its housing socket. This turns the wear process inward toward the vertical lever itself-an expensive, structurally vital forged or cast component whose replacement demands extensive downtime [21].

Consequently, the realization of maintenance-free hinge nodes-capable of surviving the entire designated operational lifecycle of a mine hoist without mid-term bushing replacements-stands as a critical objective for modern mining and transport engineering [22]. To achieve this, it is necessary to move away from empirical material selection and instead conduct comprehensive, scientifically rigorous comparative tribological evaluations of advanced self-lubricating composites under strictly controlled boundary states.

The aim of this study is to perform a systematic tribological analysis of the friction and wear kinetics of four candidate materials: SCh-15 gray cast iron, traditional bronze, grade 45 steel with an engineered $MoS_2$ solid lubricant coating, and a specialized porous iron-graphite composite modified with molybdenum (ZhGr3M). By mapping their friction coefficient dynamics, mass loss profiles, and geometric crater degradation patterns under equivalent boundary constraints, this paper establishes a scientifically substantiated foundation for upgrading critical lever-hinge mechanisms, extending overhaul intervals, and ensuring stable braking drive efficiency.

## 1. Researh methodology

Tribological studies were conducted using a ball-on-disk friction system on a Microtest tribometer (Microtest, SA, Madrid, Spain, Figure 2) under the following experimental conditions:

- sliding distance – 100 m;
- sliding speed – 150 rpm;
- trajectory radius – 2 mm;
- load – 10 N;
- test temperature – 22.3°C;
- time – 27 min.

**Fig. 2. -** Microtest tribometer

For the experiment, round specimens were made from the antifriction materials discussed above.

A hardened AISI 52100 stainless steel ball with a diameter of 4 mm and a hardness of 64 HRC was used as an indenter.

Before tribological testing using the ball-on-disk friction scheme (Figure 3), the disc-shaped specimens were subjected to preliminary mechanical treatment and surface preparation.

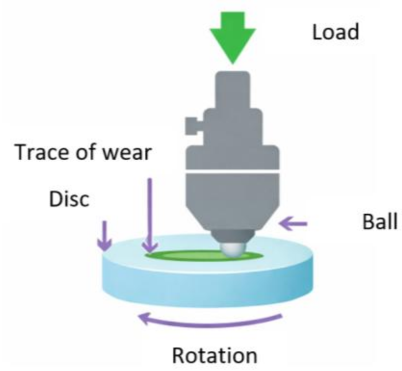



**Fig. 3.** - Ball-on-disk friction diagram

The specimen working surfaces were successively ground and polished to achieve a uniform mirror surface with minimal roughness, eliminating the influence of macroscopic irregularities on the test results according to the methodology (GOST 23.208–79). After mechanical processing, the specimens were degreased in an ultrasonic bath using ethyl alcohol and dried at room temperature.

The specimen was mounted in the Microtest tribometer disk holder, whose design ensures rigid fixation and prevents its displacement during testing. The specimen was positioned in the holder's mounting socket so that its working surface was strictly perpendicular to the load axis of the counterbody. The center of the specimen was aligned with the tribometer's rotation axis, ensuring the formation of a closed annular friction path of a specified radius.

The specimen was secured using the holder's clamping mechanism (screw or clamp type), ensuring uniform distribution of force across the entire contact area between the specimen and the supporting surface of the holder. The tightening torque of the clamping elements was selected to prevent both sample slippage and deformation, which could lead to distorted measurement results.

After mechanical clamping, the alignment and horizontality of the specimen's working surface relative to the plane of rotation were checked. This was done visually and using the tribometer's indicator equipment. Permissible surface runout deviations did not exceed the values recommended by the equipment manufacturer, ensuring stable contact conditions throughout the entire test cycle.

A counterbody, a standard 6 mm diameter ball made of AISI 52100 (100Cr6) steel, was installed in the upper holder of the tribometer and secured according to the manufacturer's instructions. After installing the counterbody, the ball was preliminarily applied to the specimen surface without load to precisely position the contact zone at the specified radius of the friction path.

Before the main experiment, the system was calibrated using a normal load, after which a specified load of 10 N was applied. Only after contact conditions had stabilized was the specimen rotated at a set sliding speed of 150 rpm. The test temperature was controlled and matched to room temperature (22.3°C).

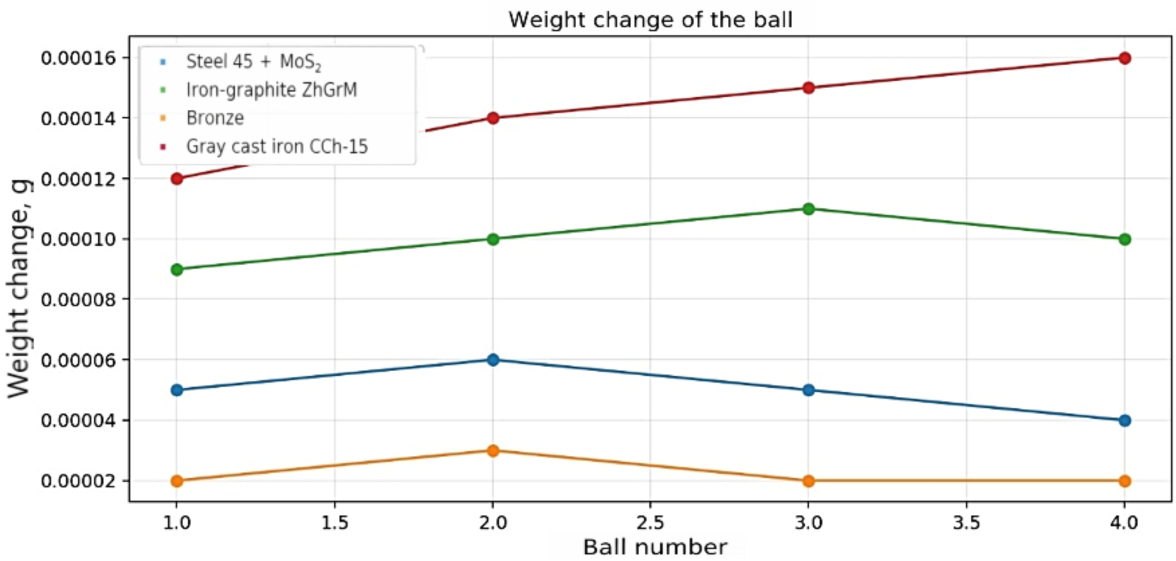
The degree of wear of the overlay material was assessed by weighing the test specimens before and after testing on an analytical balance (Figure 4).

**Fig. 4. -** Laboratory scales AS 60/220.R2 PLUS Analytical Balance

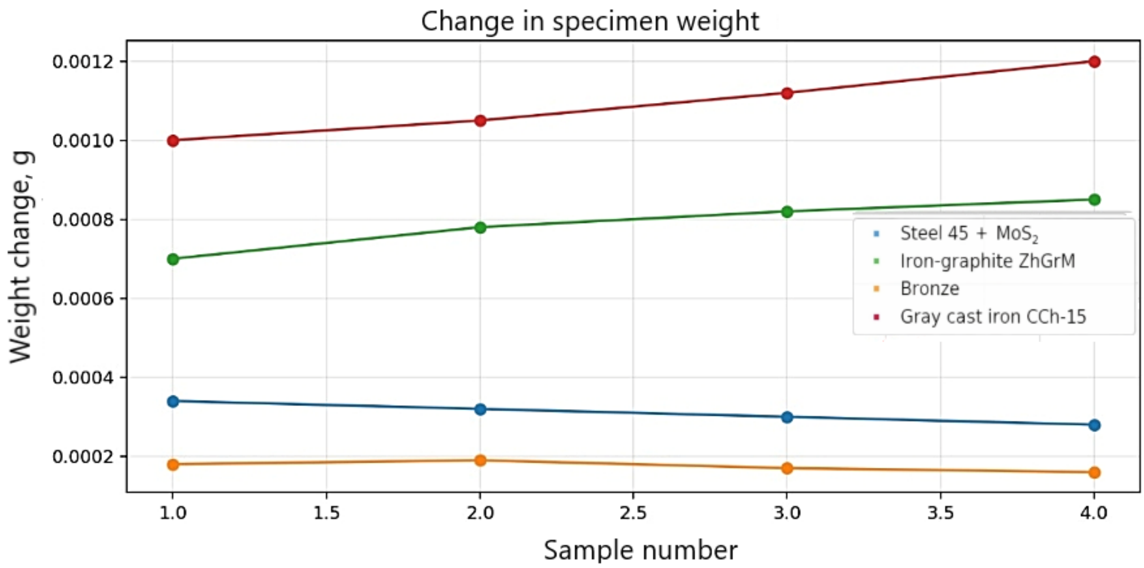
Ball weight loss was recorded on a laboratory scale with an accuracy of 0.00001%, and sample weight loss was recorded with an accuracy of 0.001%.

## 2. Results and Discussion

The resulting dependences of sample weight change on sample and ball mass change for each antifriction material are shown in Figure 5.




a)




b)

a) change in ball mass for antifriction materials, b) change in sample weight for antifriction materials

**Fig.5. -** Change in sample and ball mass for each antifriction material

Figure 6 shows the dependence of the friction coefficient on the counterbody travel distance during tribological testing.

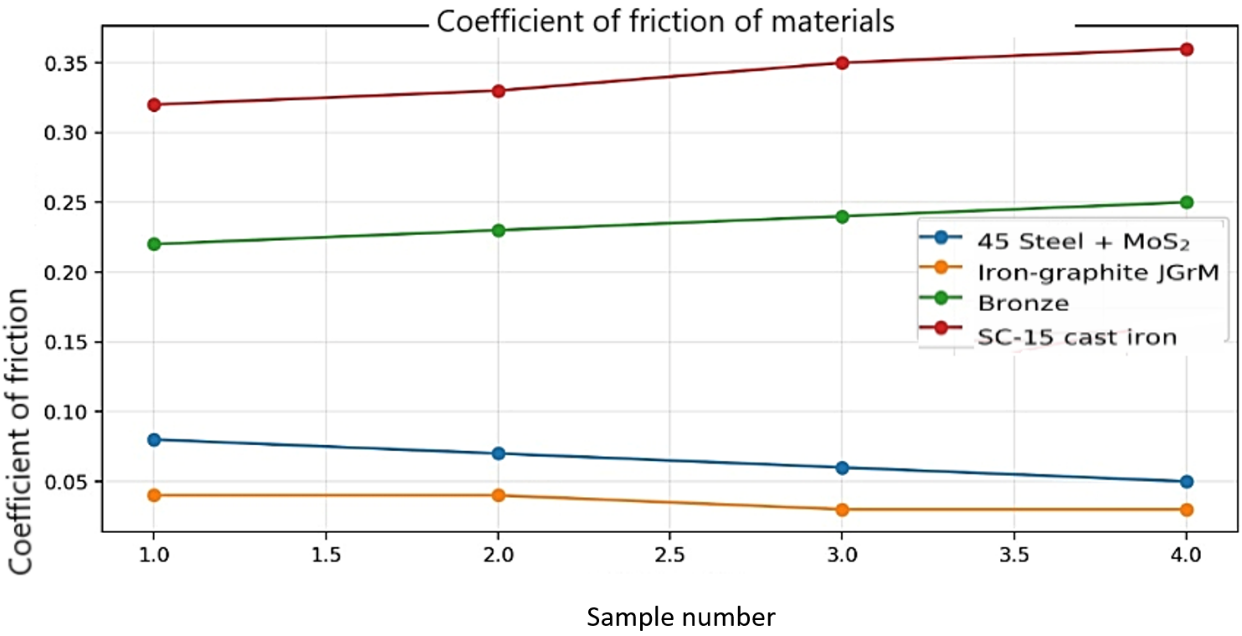



**Fig. 6. –** Dependence of wear area on wear time

It was found that wear crater area increases linearly with wear time. The largest crater area is observed for the gray cast iron surfacing material, while the smallest crater area is observed for the ZhGr3M iron-graphite with molybdenum.

To evaluate the wear resistance of antifriction materials, the dependence of the friction coefficient on the friction path was determined (Figure 7).

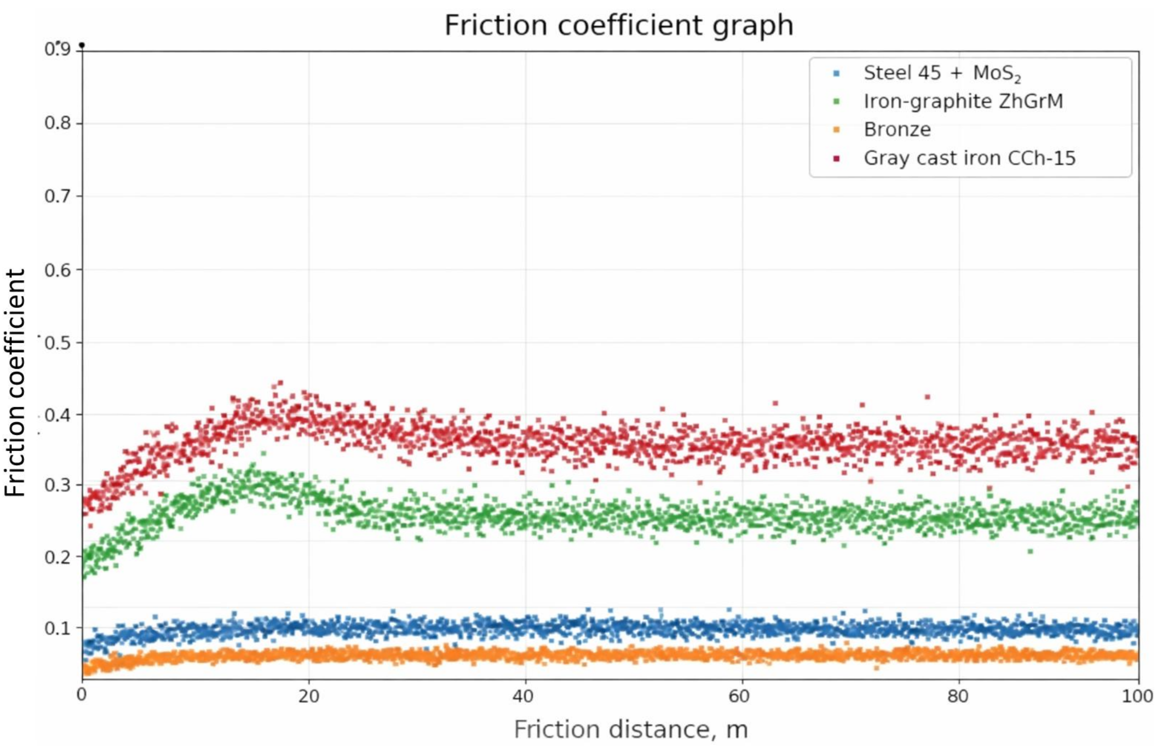



**Fig. 7 -** Dependence of the friction coefficient on the counterbody travel distance during tribological testing

The friction coefficient over a distance of 100 m was found to be 0.28 to 0.41 for gray cast iron SCh-15; 0.16 to 0.3 for bronze; 0.06 to 0.08 for grade 45 steel coated with $MoS_2$ and 0.01 to 0.05 for iron-graphite with molybdenum ZhGr3M.

The tribological test results are presented in Table 1.

**Table 1.** Experimental results

| Sample number | Change in the weight of the ball after the experiment, g | Change in sample weight after the experiment, g | Coefficient of friction | Friction path, m |
|---|---|---|---|---|
| Gray cast iron SCH-15 | 0,00009 | 0,00054 | 0,354312 | 100 |
| Bronze | 0,0001 | 0,00097 | 0,265334 | 100 |
| Steel 45 coated with $MoS_2$ | 0,00002 | 0,00106 | 0,085334 | 100 |
| Iron-graphite with molybdenum ZhGR3M | 0,0001 | | 0,044052 | 100 |

Analyzing the data in Table 1, we can conclude that the most wear-resistant antifriction material is iron-graphite ZhGr3M.

**Conclusions**

Based on the presented results of tribological tests and analysis of the operation of the lever-hinge mechanism of the braking system of lifting equipment, the following key conclusions can be drawn:

1) The operation of the articulated linkage brake mechanism of the winding machines at the mines studied (Kamyshinskaya and Artemyevskaya) is subject to harsh operating conditions. Due to frequent starts and stops and extreme radial forces (80-150 kN) in the pin-bushing pair, hydrodynamic lubrication is completely impossible. Operating the unit under boundary friction leads to adhesive wear and fretting corrosion activated by mine dust. Even minimal bushing wear (0.5 mm) distorts the lever geometry, causes edge pressure, reduces brake response, and can lead to pin fatigue failure or a loss of up to 30% of the drive energy;
2) Laboratory tests using a Microtest tribometer using a ball-on-disk design allowed us to objectively evaluate the performance of four bushing materials: SCh-15 gray cast iron, traditional bronze, grade 45 steel with a $MoS_2$ coating, and ZhGr3M iron-graphite with molybdenum;
3) SCh-15 gray cast iron demonstrated the worst results. It had the highest friction coefficient (0.28 to 0.41) and the largest wear crater area. Despite its widespread use, bronze is inferior to modern alternatives (friction coefficient 0.16 to 0.3) and is susceptible to plastic deformation under impact;
4) Steel 45 with a molybdenum disulfide coating demonstrated high friction reduction (0.06 to 0.08), preventing metal seizure during prolonged idle periods under load;
5) Iron-graphite with molybdenum ZhGr3M has been recognized as the most wear-resistant and promising material for brake system bushings. In experiments, it provided a minimal wear crater area and a record-low friction coefficient, ranging from 0.01 to 0.05. This is due to its porous structure and the presence of a solid lubricant, which creates a reliable separating layer at the molecular level;
6) The use of iron-graphite ZhGr3M bushings instead of the standard iron-graphite PA-ZhGr3 or bronze minimizes play in the hinges, eliminates peak dynamic shocks on the lever chain, and stabilizes the brake drive efficiency at ~0.92-0.95. This is an important step toward creating maintenance-free hinge assemblies in mining engineering.

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**Information of the authors**

**Nurzhanova Oxana Amangeldyevna**, PhD, associate professor, Abylkas Saginov Karaganda Technical University
**e-mail:** o.nurzhanova@edu.ktu.kz

**Boiko Sergey Borisovich**, m.t.s., director, Science technology centre Vostoktechnoservis LLP
e-mail: boiko@ntcvts.kz

**Berg Alexandra Sergeevna**, PhD, senior tutor, Abylkas Saginov Karaganda Technical University
e-mail: a.berg@edu.ktu.kz

**Mukhitova Adelia Erzhanovna**, assistant, Abylkas Saginov Karaganda Technical University
e-mail: a.mukhitova@edu.ktu.kz