Наведені результати теоретичних та експериментальних досліджень впливу зовнішнього магнітного поля на зміну параметрів зчеплення в контакті намагнічених сталевих тіл кочення. В теоретичних дослідженнях запропонована математична модель розрахунку енергії взаємодії, сили адгезії, тертя і коефіцієнта зчеплення між такими тілами. Приведена методика і результати експериментальних досліджень впливу зовнішнього магнітного поля на коефіцієнт зчеплення у фрикційній моделі контакту «колесо залізничного локомотива – рейка»

Ключові слова: сила тертя, коефіцієнт зчеплення, зовнішнє магнітне поле, тіла кочення, магнітострикція

Приведены результаты теоретических и экспериментальных исследований влияния внешнего магнитного поля на изменение параметров сцепления в контакте намагниченных стальных тел качения. В теоретических исследованиях предложена математическая модель расчета энергии взаимодействия, силы адгезии, трения и коэффициента сцепления между такими телами. Приведена методика и результаты экспериментальных исследований влияния внешнего магнитного поля на коэффициент сцепления во фрикционной модели контакта «колесо железнодорожного локомотива – рельс»

Ключевые слова: сила трения, коэффициент сцепления, внешнее магнитное поле, тела качения, магнитострикция

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RESEARCH INTO FRICTIONAL INTERACTION BETWEEN THE MAGNETIZED ROLLING ELEMENTS

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1. Introduction

A contact interaction between metal rolling elements is a rather widespread example of the interaction between conjugated parts of various technical systems. For example, the interaction of rolling elements with rings in rolling bearings, rollers of various tracking mechanisms or drives, steel crane wheels with crane tracks, rolling stock wheels of railways with rails. Requirements for friction and adhesion characteristics depend on the purpose of a system or a mechanism in which rolling of steel elements is used. In some cases, it is necessary to minimize friction in order to reduce losses in mechanisms, for example in rolling bearings. In other cases, such as a "wheel-rail" contact, it is necessary to strive for an increase in adhesion coefficient at a contact area limited by a deformation magnitude and having small dimensions.

Taking into account a wide application of contact interaction of this kind, the actual task is the search for methods of friction and adhesion control. The effect of such methods should affect characteristics of friction interaction in a certain range, which should be rational for a particular type of mechanism. Since most of engineering products containing rolling elements are made of ferromagnetic materials, the most promising from the point of view of friction control are the methods of influence on tribological contact by a magnetic field. The studies that are undertaken in this area are often empirical in nature. In addition, proposed solutions are complex for their implementation, this fact generally limits their use in practice.

2. Literature review and problem statement

The problem of friction control in a contact of steel rolling elements is a subject of interest to many scientists over a long period of time. From the tribology point of view, friction as a process consists of a number of physical, chemical, and mechanical processes that mainly occur in the surface layers of contacting elements. It is also well known that there are two main types of interaction – mechanical and molecular when the process of friction occurs [1, 2]. The term "molecular component of friction" was introduced at the beginning of the 20th century [2], but, regarding a dry contact of metallic elements, it is more correct to operate with the term "atomic ...". Various factors affect the level and ratio of mechanical and molecular components of frictional force. Such factors include a structure and properties of contacting elements materials, a presence of a third element and its properties, a shape and a size of contacting surface, surface roughness, temperature, relative speed of displacement, and so on [1, 2].

By analogy with development of tribology, friction control methods also developed. All attention was paid to the effect on a mechanical component of a friction at the initial stage. As a result, all known methods in this area are aimed at improving the geometry of a contact [3, 4], formation of rational microgeometry of contacting surfaces [5, 6], providing necessary mechanical properties to materials of contacting elements [7, 8], optimization of external load, rolling speed, temperature in terms of a shape and a size of contact area [3, 9]. The enumerated methods were sufficiently studied and have been widespread in engineering, therefore the main reserves of rolling friction control are in the area of molecular and atomic components.

One author proposed a phonon theory of friction in paper [10]. The main idea of this theory is that adhesion forces depend on vibrations of atoms (phonons) on the actual contact area. A change in vibrations of atoms leads to a significant change in the interaction between contacting surfaces. Vibrations of these phonons can be influenced by using additional external energy, for example, thermal, magnetic, or electric energy. The presented work is one of the first to reveal physical foundations of atomic friction between steel rolling elements, but it is only of a theoretical nature. The molecular component of rolling friction (in the presence of a third body) was investigated in [11–13]. This experimental study indicates an important role of the molecular component, but does not disclose possibilities of friction control by supply of an external energy of electromagnetic nature.

It becomes clear during detailed examination of the physical phenomena occurring in a contact of steel rolling elements, for example, wheels of a locomotive and a rail, that the realization of traction force occurs at rather small contact areas. The force interaction that occurs when contacting surfaces approach to the level of atomic roughness becomes significant if one considers large contact pressures. That is, in the range where the atomic component of friction force prevails [10, 14]. The nature of binding forces will be electromagnetic in this case, and this means that the methods of influence on connecting forces must be of the same nature. Therefore, it is not a coincidence that the development of modern methods of control of friction and adhesion in rolling elements are based on the use of electric and magnetic fields [15, 16].

An increase in the adhesion coefficient is observed when passing directly through a contact of electric current and a magnetic field according to the results of studies [15]. This method, in contrast to the traditionally applied method of adhesion increase by the use of sand, does not lead to intensive deterioration of contacting elements. However, it apparently requires considerable energy consumption, since the density of current, which is passed through the contact, increased from 68 A/mm^2 to 176 A/mm^2, while the magnetic field strength changed from 0.6 kA/m to 7.4 kA/m, in order to achieve increased adhesion.

Paper [16] shows how the coefficient of adhesion behaves when a magnetic field generated by permanent magnets is applied to rolling elements. The study implied the following: a different number of permanent magnets was placed along the side surfaces of one of contact rollers. Further, a testing under conditions of different environment, rotation speeds and roughness was conducted. The behavior of adhesion forces was observed when a contact occurred in the presence of water or oil. The effect of the magnetic field caused an increase in the coefficient of adhesion in the first and second cases. However, it was not possible to achieve the required values of the coefficient of adhesion under conditions of dry contact. The change in the speed of rotation did not produce a particular effect on adhesion parameters. A change in the roughness parameter from high to low led to a decrease in the coefficient of adhesion by several times.

Expediency of studies in the field of methods of influence on the parameters of adhesion in a contact of metallic rolling elements is obvious, since it is possible to achieve the desired changes [15, 16]. However, high energy consumption and complexity of the implementation of these methods necessitate further research in this direction.

3. The aim and objectives of the study

The aim of present study was to examine the effect of an external constant magnetic field on a change in the adhesion parameters in a contact of magnetized steel rolling elements. This study should provide a possibility to justify parameters of the rolling friction control method in various machine-building products.

To achieve the objective, the following tasks were set:

– to conduct theoretical study into effect of an external magnetic field on the atomic component of rolling friction taking into account magnetostrictive phenomena;

– to determine experimentally dependences of the influence of an external magnetic field on frictional characteristics in a simulated rolling contact (using a “wheel-rail contact” as an example).

4. Materials and methods for studying the effect of an external magnetic field on frictional characteristics of steel rolling elements

4. 1. Examined materials and the equipment used

The investigations were carried out at a bench (Fig. 1), its design and characteristics were described previously in paper [17]. The bench was designed to study frictional characteristics of rolling elements according to the “disk-plane” scheme. A disk has a spherical shape of a rolling surface, which makes it possible to recreate a process of rolling of a wheel along a rail under conditions of a single-point contact, when the contact area has an elliptical shape.

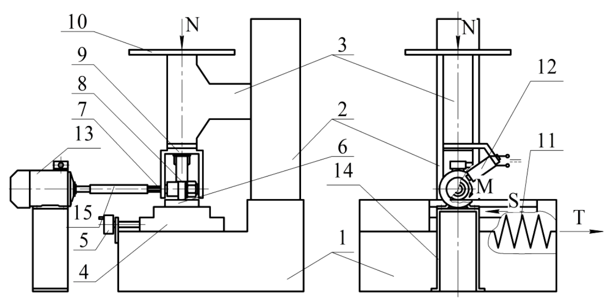

Fig. 1. Schematic of a laboratory bench: 1 — stand; 2 — column; 3 — bracket; 4 — object table; 5 — flywheel; 6 — contact plane; 7 — power shaft; 8 — contact roll; 9 — roll stand; 10 — loading plane; 11 — springs; 12 — electromagnet; 13 — electric motor; 14 — base of electric motor; 15 — muff coupling

In order to create conditions that are maximally close to an actual contact, the samples were made of materials used in the production of wheels and rails of rolling stock: disc – Steel 2 GOST 398-2010, plane – Steel M76 GOST R 51685-2000.

4. 2. A method for determining characteristics of the contact parameters

The study method consists of the implementation of a consecutive set of actions. First, a normal load N is set on contact roll 8 using roll stand 9 and loading plane 10. Then, a torque moment M is created by turning on electric motor 13 on a power shaft and this starts translational motion *S* of contact plane 6. The plane is attached to object table 4 rigidly. Springs 11 are placed under object table 4, they prevent this movement. With the further movement of contact plane 6, there comes a moment when the normal load N is not enough to contradict forces of springs 11. Then, contact roll 8 slips relatively to contact plane 6, resulting in the adhesion break.

Displacements of object table 4 are registered with a linear potentiometer, which is attached to stand 1. The potentiometer is connected to a personal computer via a special cable. Object table 4, springs 11, the potentiometer, the cable and the personal computer are collectively a digital dynamometer. This dynamometer makes it possible to record a change in the resistance of the potentiometer in the form of a chart that describes the dependence of frictional force on the movement of the object table. Frictional force drops sharply at the moment when the adhesion failure occurs and its peak value is registered at the same time. The coefficient of adhesion in this case can be calculated as the ratio of maximum tension force T to the magnitude of normal load *N*.

A DC electromagnet 12 was used for magnetization of steel samples by an external field. It is a solenoid with a steel core. A number of measurements of friction rolling force were carried out to assess influence of the degree of magnetization on characteristics of adhesion between the disk and the plane. Further, the coefficient of adhesion was calculated according to the procedure given in [17]. During the experiment, a voltage in the winding, as a consequence of the value of magnetic induction, was changed stepwise from zero to the maximum accepted value. The values of magnetic field parameters were recorded using a Hall sensor.

5. Results of theoretical and experimental studies

Nodes of crystal lattices start interacting with each other when contacting surfaces approach the level of atomic roughness. There are metal ions surrounded by a socialized electron gas in the nodes of the crystal lattices of metals, according to the definition of a metal bond [18]. Then the force and energy of interaction of contacting elements depend on a type and parameters of the crystal lattice, and also on the actual contact area. In a general case, the interaction energy can be determined using the Lennard-Jones potential – a simple model of the pair interaction of charged particles. The model describes a dependence of interaction energy of two particles on the distance between them [19]. The model in its usual notation takes the form:

$$U(r)=4\varepsilon\left[\left(\frac{\sigma}{r}\right)^{12}-\left(\frac{\sigma}{r}\right)^{6}\right], \quad (1)$$

where *U(r)* is the total interaction energy of two particles; ε is the depth of a potential well; *r* is the distance between centers of particles; σ is the value of *r* for which *U(r)*=0. The parameters ε and σ are characteristics of atoms of the corresponding substance. They were calculated for iron by the recommendations of [20]. The essence of the model is that it takes into account both attraction forces of particles and repulsion forces, which manifest themselves in different degrees and essentially depend on the distance between particles. Also, by employing this model, it is possible to calculate at what value of *r* the interaction energy will be zero. The chart of a change in the energy of interaction of iron atoms on the distance between them in a crystal is shown in Fig. 2.

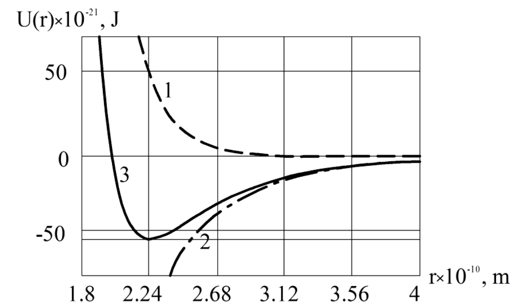

Fig. 2. Change in interaction energy U of two iron atoms caused by the distance between them, *r*: 1 — repulsion energy; 2 — attraction energy; 3 — total energy

Data on the distance between centers of atoms given above are sufficient to calculate the force of interaction between these particles. The strength of the interaction can be calculated from the following formula

$$F(r)=\frac{dU(r)}{dr}. \quad (2)$$

The interaction force between atoms at the nodes of the iron crystal lattice was determined by using data from Fig. 2 and dependence (3). It is shown in the chart in Fig. 3.

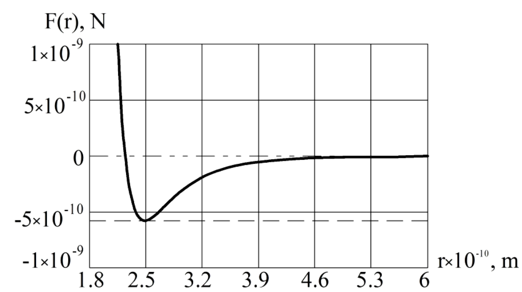

Fig. 3. Dependence of interaction force *F* of two atoms on the distance *r*

The obtained values of energy and interaction forces for two atoms at the nodes of the crystal lattice of iron make it possible to study the total force of interaction between these atoms in a unit cell. The total interaction force in this case will take the form of the total interaction force between each node of the crystal lattice of contacting elements.

Fig. 4 shows how two sides of crystal lattices of contacting elements interact with each other: each node of the crystal lattice of the first element has the force of interaction with each node of the crystal lattice of the second element. The force of interaction will vary from a maximum to a minimum at a distance equal to half the period of the crystal lattice *tx, ty* (Fig. 4) since it depends on the distance between atoms that are at the lattice nodes. Therefore, we assume in the calculation that one crystal lattice is displaced along the X axis by some distance *k* from the other. There is no displacement along the Y axis.

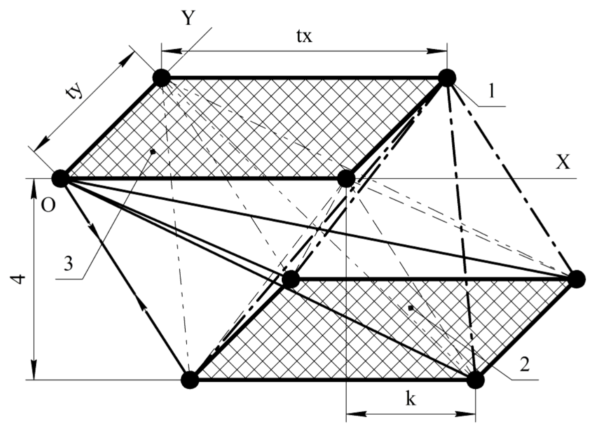

Fig. 4. Calculation scheme to determine the total interaction force: 1 – iron atom; 2 – a side of the crystal lattice of the second element; 3 – a side of the crystal lattice of the first element; 4 – distance between contacting elements

In this case, a formula for calculating the total interaction force between two contacting sides will take the form

$$F(k)=\sum_{y=0}^{n}\sum_{x=0}^{n}F\left[\sqrt{(tx\times x+k)^2+(ty\times y)^2+h^2}\right]+$$
$$\sum_{y=0}^{n}\sum_{x=0}^{n}F\left[\sqrt{(tx\times x-k)^2+(ty\times y)^2+h^2}\right]-$$
$$-F\left(\sqrt{k^2+h^2}\right)+\sum_{y=1}^{n}\sum_{x=1}^{n}F\left[\sqrt{(tx\times x+k)^2+(ty\times y)^2+h^2}\right]+$$
$$+\sum_{y=1}^{n}\sum_{x=1}^{n}F\left[\sqrt{(tx\times x-k)^2+(ty\times y)^2+h^2}\right], \quad (3)$$

where *tx, ty* are the parameters of crystal lattice; *h* is the distance between contacting elements; *k* is the displacement of lattice nodes relative to each other, $0\le k\le tx/2$; *n* is the number of atoms in a side of the crystal lattice of iron, $n=4$.

A change in the total interaction force from the displacement of crystal lattices relative to each other is shown in the chart (Fig. 5). The data obtained in Fig. 3 are accepted for the calculation. We assume that $tx=ty=h$

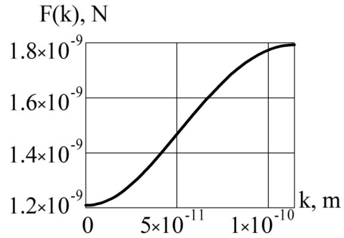

Fig. 5. Dependence of the total interaction force *F* between the sides of crystal lattice on the displacement *k* along the X axis

Once we have the value of the total interaction force, it is possible to calculate specific attraction force between contacting surfaces. The formula for its calculation will take the form

$$F_{sp}(k)=\frac{F(k)}{tx\times ty}. \quad (4)$$

Fig. 6 shows the chart of values of specific attraction force.

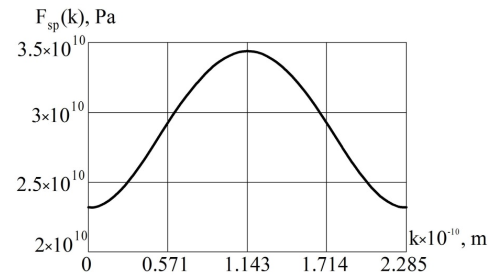

Fig. 6. Dependence of specific attraction force F_{sp} of the contacting surfaces on displacement *k* along the X axis

The dependence for calculating specific friction force will take the form

$$Fm=\frac{\left[\int_{0}^{\frac{tx}{2}}\left(F_{sp}(x)-F(tx)\right)\times \mathrm{d}x\right]}{\frac{tx}{2}}. \quad (5)$$

In dependence (5), a denominator is the work of friction force, that is, a work done by the friction surface when it is displaced by magnitude *k* relative to the other surface.

The coefficient of adhesion will be calculated as the ratio of the maximum specific friction force in the contact area to the normal load acting on the contact. The formula for calculation will take the form

$$f=\frac{Fm\times S_c}{G_l}, \quad (6)$$

where S_c is the contact area; G_l is the value of normal load.

The above model suggests that the adhesion forces between two contacting elements can be changed by changing the distance between lattice nodes during their interaction. Therefore, it is necessary to take into account the phenomenon of magnetostriction, which is associated with a change in the parameters of crystal lattice [21, 22], when considering the interaction of crystalline solids during magnetization. This is especially important for the steel rolling elements, which are brought together to the level of atomic roughness.

Thus, by changing parameters of magnetization, it is possible to change the values of parameters of the crystal lattice of magnetized elements simultaneously, which will lead to a change in the interaction force between them during contact. Friction coefficient values for the entire possible range of interatomic distance variation in the crystal lattice under the influence of an external magnetic field were calculated using dependences (5) and (6), as well as the known values of magnetostriction of ferromagnets [21, 22] (Fig. 7). The calculation was performed on the example of contact between a wheel of a locomotive and the rail, which is why the values of S_c and G_l were taken based on data from paper [15].

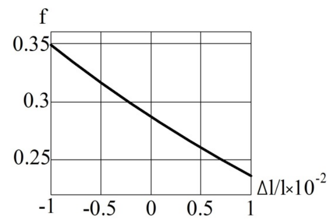

Fig. 7. Dependence of adhesion coefficient f on the magnitude of magnetostriction Δb/l

A number of experimental studies were carried out to examine effect of a change in the induction of magnetic field on the adhesion coefficient between steel rolling elements according to the procedure described above. Results of experimental studies are shown in Fig. 8.

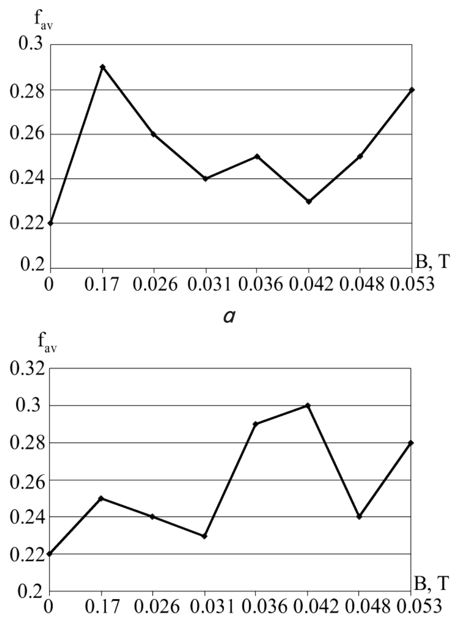

Fig. 8. Dependence of the average value of adhesion coefficient f_{av} on the induction of magnetic field B: *a* – "direct polarity" of electric current; *b* – "reverse polarity" of electric current

By analyzing the charts shown in Fig. 8, it is possible to argue that the coefficient of adhesion varies non-linearly depending on a change in the induction of magnetic field. In addition, there is a significant difference in the results when current is passed with a change in the polarity relative to contacts of a solenoid.

6. Discussion of results of studying the effect of an external magnetic field on the adhesion characteristics of steel rolling elements

Theoretical studies that we carried out made it possible to determine energy and force of interaction of contacting metal elements, which are brought together to the level of atomic roughness. A mathematical model is proposed and calculations of force and coefficient of adhesion in a contact of rolling elements are performed taking into account the magnetostriction effects. According to the studies, magnetization of metallic elements leads to a change in the coefficient of adhesion between them, both to the greater and to the lower side, Fig. 7, due to the manifestation of a magnetostrictive effect in the crystal lattice of surface layers of a metal. Calculations are performed on the example of contact "wheel of a locomotive – rail"; the proposed model, however, as well as the calculation technique, can be applied for analogous tribological systems where rolling friction is implemented.

Results of experimental studies show that the impact of magnetic field significantly affects the atomic component of adhesion forces, which is confirmed by the results of theoretical studies. According to Fig. 8, adhesion is increased to 36.4 % at "direct polarity" and up to 31.8 % with "reverse polarity". Moreover, in the first case the maximum effect is observed in the region of high fields, while in the second – in the region of low fields. Apparently, this is due to the predominant location of the sides of iron crystals in the surface layers of model rolling elements.

The results obtained could be used to implement the method of control over adhesion in rolling elements, however, in order to implement them, further studies are required under conditions of influence from different media (the application of so-called "third body"), varying external loads and velocities of relative displacement.

7. Conclusions

1. A mathematical model is developed to determine the atomic component of force and the coefficient of adhesion in a contact between steel rolling elements. In contrast to those already existing, the given model takes into account a change in the interatomic distance in a crystal lattice due to magnetostrictive effects and it could be applied to predict rolling friction parameters of a wide range of engineering products.

2. The calculation, based on the developed model, shows on the example of contact "wheel of a locomotive – rail" the possibility of both increasing and decreasing the adhesion coefficient, which agrees well with the physical concepts of magnetostriction phenomena in ferromagnets. The calculation performed also partially confirms the available experimental material on the effect of external magnetic field on the friction parameters between metallic elements.

3. Experimental studies into process of friction between steel rolling elements established that the magnetization of rolling elements leads to an increase in the adhesion forces to 36.4 %, which is significant from the point of view of development and creation of methods for adhesion control in similar technical systems.

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