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# INCREASING THE WEAR RESISTANCE OF HEAVY LOADED FRICTION UNITS OF ANTI-FRICTION GAS THERMAL COATINGS


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***Purpose.*** *The purpose of this study is to establish technological conditions and parameters for obtaining materials for improving the performance of machine parts under conditions of heavily loaded friction units due to quasi-tribosystems of gas thermal sprayed anti-friction layers.*

***Research methods.*** *Priori data were used in combination with our own scientific developments of the dependences of the influence of the chemical composition of gas thermal sprayed anti-friction layers on the physical and mechanical properties of the surface layer of the material, which is destroyed under tribosystem conditions.*

***Results.*** *On the basis of the theoretical and practical scientific research, a set of relevant knowledge has been obtained, which makes it possible to determine the main criteria requirements for obtaining anti-friction layers and graphically describe the characteristics of the alloy and show the correlations of the parameters with each other. The positive role of aluminum as a soft component of anti-friction pseudoalloys, which is well sprayed by thermal metallization at an affordable cost, has been experimentally confirmed. It has been proven that gas thermal coatings in the form of pseudoalloys, consisting of particles with different physical and mechanical properties of materials, can have up to 2–3 times higher wear resistance compared to single-component coatings from materials included in the composition.*

***Scientific novelty.*** *Theoretical and practical scientific research with the reproduction of system analysis to increase the resistance to destruction under the conditions of quasi-tribosystems of gas thermal sprayed antifriction layers is given. It is shown that in order to ensure a good running in of the contacting surfaces in the friction zone and particles of hard material with high wear resistance and resistance against sticking with the counterbody, anti-friction pseudoalloys of coatings should contain zones of material particles with lower hardness to comply with the Charpy principle. It has been determined that when spraying composite wires for application as a solid component of anti-friction coatings, it is possible to use particles of alloying elements that form intermetallic compounds or phase components of alloys with a high hardness during melting. A comparative analysis showed that two-component coatings deposited with composite wires are characterized by higher hardness and wear resistance under high contact pressures compared to coatings of the same composition deposited with different types of solid wires.*

***Practical value.*** *The obtained results allow, within the framework of technical and technological accuracy, which is necessary in the practical engineering forecasts, to determine the physical and mechanical properties of wear resistant gas thermal sprayed anti-friction layers under conditions of quasi-tribosystems. Thus, in comparison with cast antifriction materials of the same composition, anti-friction layers obtained by thermal metallization have a 1.5–1.8 times higher wear resistance.*

***Key words:*** *wear resistance, hardness, quasi-tribosystems, anti-friction layer, gas thermal coating, spraying, pseudoalloy.*

## Introduction

To improve the performance of machine parts with heavily loaded friction units due to the availability of applications in the repair, restoration, hardening of working surfaces, the technologies of gas thermal spraying of anti-friction layers are becoming more and more widely used [1].

First of all, this is due to the fact that the methods of gas thermal spraying, despite the metallurgical compatibility of the material of the part, provide a wide range of coating thickness from 0.1 mm to 8 mm. In addition, an insignificant melting zone of the working surface and a slight overheating of the product cause the absence of critical deformations. This makes it possible to expand the technical and technological range of applying


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coatings on products without limiting their thickness to dissimilar materials from pure metals to alloys and non-metallic materials of ceramics, glass, and wood.

The problem of gas thermal coatings lies in their insufficient technological adhesion to the friction surface, limited properties that are related to the strength and plasticity of sprayed layers compared to welded ones. The analysis of the operating conditions showed that, taking into account the low adhesive and strength properties of gas thermal coatings, it is most appropriate to apply them to parts working under conditions of corrosion destruction, anti-friction layers for work under conditions of sliding friction, surface wear, which provide press and running fits during multi-cycle fatigue failure .

Therefore, the materials must provide high wear resistance and a low coefficient of friction of the sprayed surfaces of parts, a low tendency to the development of adhesion processes between contacting surfaces with limited access of lubricant to the friction zone and destruction of the oil film, as well as high strength and adhesive properties. Also, the materials must have high heat capacity and thermal conductivity to ensure good heat removal from the friction zone, to prevent overheating of the coating and destruction of the oil film. Therefore, in this work, the possibility of applying high-quality coatings from anti-friction pseudoalloys, which will be suitable for work in conditions of sliding friction at high contact pressures and limited supply of lubricants, was studied by the electric arc method.

In the literature, there are data on the use of several types of anti-friction pseudoalloys, the most famous of which are copper-lead, copper-steel, and steel-aluminum compositions [5, 13]. The work studied the workability of pseudoalloys with a composition of 70 % Cu + 30 % Al, 85 % Fe (low-carbon steel) + 15 % Cu, 75 % Cu + 25 % Pb at sliding speeds of 3 – 4 m/s and loads up to

294 × 104 N/m$^2$. Under such working conditions, an oil film was formed and preserved in the friction zone, which ensured high performance and good tribotechnical properties of all sprayed pseudoalloys. The high performance of pseudoalloys compared to cast materials is due to the fact that, like metal-ceramic materials, they have a porous heterogeneous structure. The presence of recesses and pores provides favorable conditions for maintaining the oil film in the process of friction even after stopping the supply of lubricant. Porosity promotes wetting and absorption of wear products. Therefore, pseudoalloys run in quickly and show little tendency to burr formation compared to cast anti-friction materials.

A significant improvement in the operational characteristics of the sprayed layers can be obtained through the application of multi-component coatings with a wide range of doping. This can be achieved when using polymetallic composite wires, which have a metal shell and a core in the form of one or more metal wires of different composition, for applying metallization layers. By changing the materials of the shell and core, their mass ratio, it is possible to obtain a wide range of compositions and properties of sprayed coatings, which ensure the achievement of acceptable tribotechnical and strength characteristics of the applied layers for the given operating conditions.

## Materials and experiments

The possibility of using different compositions of two-component pseudoalloys of the Fe-Al, Cu-Fe, Cu-Al type, sprayed by the electric arc method using solid and polymetallic wires, as well as multi-component coatings of the Fe-Cu -Al type for parts operating at high contact pressures in conditions of sliding friction at low speeds and limited supply of lubricant was studied.

The wear resistance of two-component pseudoalloys of the Fe- Al, Cu-Fe and Cu-Al type, coated with solid and composite wires, was determined when working together with a steel roller made of steel 45 under conditions of limited supply of lubricant by drop method.

When determining the specified indicators, spraying was carried out on samples, the surface of which was treated by shot blasting with an acute shot with a particle size of 0.8–1.5 mm, in order to obtain a microrelief with Rz = 30–60 μm. Spraying was carried out with wires with a diameter of 1.5–1.8 mm, the speed of which was selected depending on the desired composition of the coating. Other mode parameters were supported within the following limits: arc voltage 34–38 V; spray air pressure 0.495–0.505 MPa;

The wear resistance of the coatings was determined by testing samples with a cylindrical surface according to the “shaft – clamp” scheme and samples with a flat working surface when they were worn by a roller according to the “linear contact” scheme (Fig. 1).

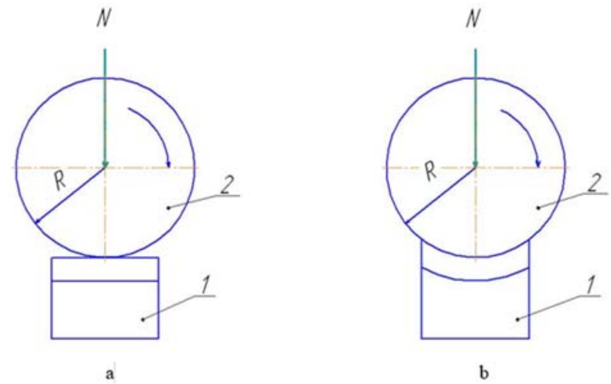


**Fig. 1.** Testing of samples according to the scheme of “linear contact” (*a*) and “cylindrical contact” (*b*)

1. Sample with metallization coating;

2. Wear roller made of steel 45

R is the radius of the roller, N is the load on the roller

The tests were carried out on a 2070CMT-1 machine with a roller with a diameter of 50 mm at a relative sliding speed of 0.392 m/s. Tests of flat samples according to the “linear contact” scheme were carried out under loads of 1250 N, 2400 N and 4800 N per 1 cm of the length of the contact line. The intensity of wear was determined by the volume of the worn pit V, related to the length L of the


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friction path. The volume of the worn pit on the sample was determined geometrically, taking into account its dimensions from the ratio:

$$V = \frac{2}{3} b \left( r - \sqrt{r^2 - \frac{b^2}{4}} \right) l,$$

where $b$ – the width of the hole, mm

$r$ – the radius of the surface of the pit, which was taken to be equal to the radius of the roller, mm

$l$ – the length of the pit, mm.

Samples measuring 10×20 mm with a concave cylindrical surface were tested according to the "cylindrical contact" scheme of the "shaft-clamp" system under loads of 1600 N, 2400 N and 3200 N, which provided a pressure on the surface of the sample of 8 MPa, 12 MPa and 16 MPa, respectively. The wear intensity was also determined by the ratio of the worn volume of the sample to the friction path. The worn volume was calculated based on the results of measuring the weight loss of the samples during tests, taking into account the specific weight of the coating.

The value of the coefficients of friction and the tendency of the sprayed coatings to develop adhesion processes with the counterbody were also evaluated. The coefficient of friction was determined by the ratio of the friction moment to the load and the radius of the wearing roller. The propensity of sprayed coatings to the development of adhesion processes with a steel roller was determined by the time interval from the cessation of the supply of lubricant to a sharp increase in the friction moment.

The strength characteristics of the coatings were evaluated based on the results of measuring their integral hardness, the adhesion strength of the coating to the surface of the sample, and the amount of internal stresses in the sprayed layer. The hardness of the sprayed layers was determined based on the results of five parallel measurements with a ball indenter using the Rockwell method on the HRB scale. The adhesion strength of the coating to the surface was evaluated using the "pin pull" method [4,9]. It is known [4] that the numerical values of the adhesion strength, determined by the "pin pull" method, depend on the pin diameter and will be larger the smaller the pin diameter is used to evaluate the adhesion strength. Therefore, this characteristic has a comparative information value for the same test conditions. Samples with pins with a diameter of 5 mm were used to determine the adhesion strength of the coatings.

A comparative assessment of the magnitude of internal stresses in gas thermal coatings was carried out by measuring the deflection of 2×20×200 mm samples after spraying pseudoalloy coatings on their surface. Before spraying, the samples were polished, shot blasted to create the necessary microrelief on the sprayed surface, and then annealed in a clamped state in a vacuum furnace to eliminate internal stresses from rolling and shot blasting.

After spraying of such samples, a deflection occurs in them, the value of which was measured with an indicator with an accuracy of 0.05 mm.

Determination of the amount of internal stresses in the sprayed layer was carried out according to the simplified Brenner-Senderoff relationship [4]:

$$\sigma_r = \frac{E_2 \delta_2}{6 r \delta_1} \left( \delta_2 + \left( \frac{E_1}{E_2} \right)^{\frac{5}{4}} \delta_1 \right), \text{МПа}$$

where $\delta_1$ is the coating thickness, m;

$\delta_2$ – thickness of the steel sample, m;

$r$ – radius of curvature of the sample, m;

$E_1$ – the modulus of elasticity of the sprayed layer, MPa;

$E_2$ – the modulus of elasticity of the material of the steel sample, MPa.

The radius of curvature of the sample was determined taking into account the value of the measured deflection h and the length of the sample $L$ from the ratio:

$$r = \frac{L^2 + 4h^2}{8h}, \text{м}$$

When calculating the value of internal stresses, the modulus of elasticity of the sample material and the modulus of elasticity of metallization coatings made of copper, aluminum, and iron (steel with a carbon content of < 0.08 %) were taken according to the existing experimental values given in works [4, 5, 10, 11].

The estimated values of the modulus of elasticity of composite coatings were obtained by additively summing the modulus of elasticity of simple substances that were part of the coating. Average calculated values obtained from the results of three parallel experiments were taken as an evaluative value of the magnitude of internal stresses for each type of coating.

**Results and discussion**

The results of the research showed that when working in conditions of sliding friction at low speeds and limited supply of lubricant, all types of sprayed pseudoalloys have several times greater wear resistance compared to single-component coatings made of copper, aluminum or iron. This regularity is preserved for all test schemes and different values of contact pressures.

When working in conditions corresponding to the "linear contact" scheme, iron-aluminum coatings showed higher wear resistance. Minimal losses have pseudoalloys with 20–30 % Al (Fig. 2). At the same time, coatings sprayed with composite wires have higher hardness and wear resistance compared to coatings of a similar composition, but sprayed using continuous wires (Fig. 3). This is caused by the presence of a significant amount of FeAl intermetallic phase in coatings sprayed with composite iron-aluminum wires, while such intermetallic is practically not detected in coatings sprayed with various types of continuous wires.


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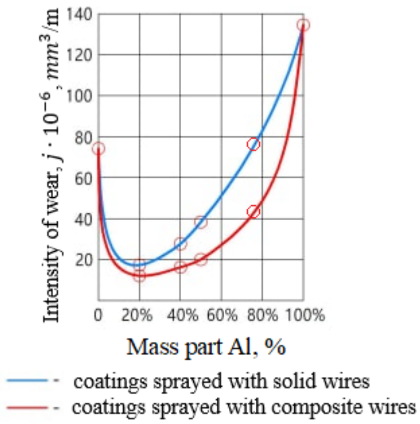


**Fig. 2.** Influence of aluminum content on the intensity of wear of Fe-Al coating in conditions of linear contact with a load of $2.4 \times 10^5$ N/m

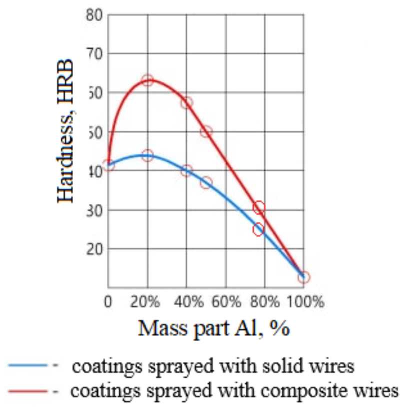


**Fig. 3.** Effect of aluminum content on hardness of Fe-Al coating

When working under the conditions of "cylindrical contact", the amount of volumetric wear of the samples is significantly higher compared to the test according to the "linear contact" scheme. This is caused by the influence of the scale factor, due to the different area of the surface areas of the sample that are in contact during the friction process, as well as the deterioration of the conditions for the lubricant to enter the friction zone with cylindrical contact at low sliding speeds. But even in the conditions of cylindrical conjugation of Fe-Al surfaces, coatings sprayed with composite wires wear out less intensively compared to layers sprayed with solid wires.

The presence of a smaller amount of the soft component in coatings sprayed with composite wires causes a higher coefficient of friction compared to coatings sprayed with solid wires, both when worn in cylindrical and linear contact conditions (Fig. 4).

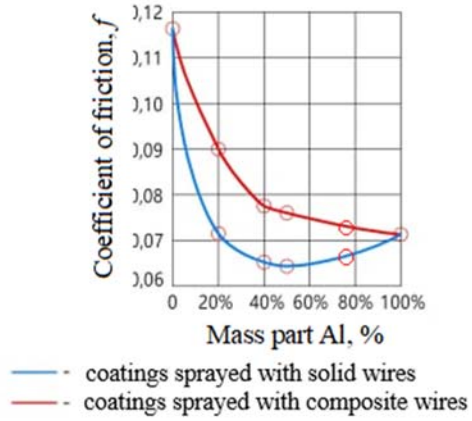


**Fig. 4.** Influence of the aluminum content in Fe-Al pseudoalloys on the friction coefficient after stopping the supply of lubricant for samples with linear contact under a load of 2.4 × 105 N/m

Coatings sprayed with composite wires can work longer without lubrication before beginning processes adhesion with the steel roller compared to coatings of a similar composition sprayed with solid wires (Fig. 5).

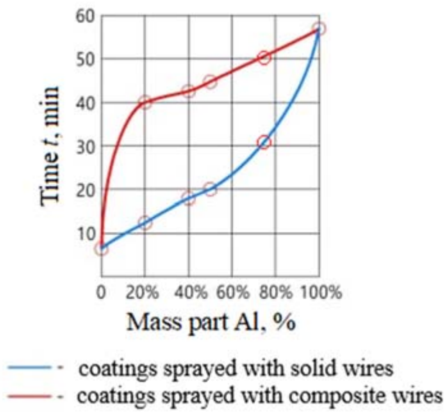


**Fig. 5.** Influence of the aluminum content in Fe-Al pseudoalloys on the time of adhesion with a steel roller after stopping the supply of lubricant for samples with linear contact under a load of $2.4 \times 10^5$ N/m

In conditions of cylindrical conjugation of the sample surfaces, this time differs by two times, and in conditions of linear contact, this difference increases to three times.

For copper-aluminum coatings, the maximum wear resistance is achieved in pseudoalloys containing 20–30 % Al. Compared to iron-aluminum coatings, copper-aluminum layers have 20–30 % lower wear resistance at high pressures in linear contact conditions. At the same time, in cylindrical conjugation, when it is difficult to get lubricant into the friction zone, Cu-Al layers are somewhat superior in resistance to wear of Fe-Al coatings, sprayed with both composite and continuous wires.


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They are less prone to the development of adhesion processes after stopping the supply of lubricant, providing twice the duration of operation of sprayed surfaces without lubrication compared to Fe-Al layers with a similar aluminum content.

Copper-aluminum compositions are easier to run in and have a lower coefficient of friction compared to iron-aluminum compositions. For tests under conditions of linear contact, this difference reaches 1.2–1.3 times, and for cylindrical conjugations 1.1–1.15 times.

In iron-copper compositions, the copper content in the amount of 20–50 % helps to increase the wear resistance at high pressures in the conditions of linear contact, but it is inferior to the wear resistance of Fe-Al and Cu-Al compositions. In the conditions of cylindrical Fe-Cu contact, coatings containing 20–50 % copper also have significantly higher wear resistance compared to one-component iron or copper coatings, but even in this case they are also inferior to the performance of Fe-Al layers.

Based on the obtained data, it was established that all types of investigated two-component pseudoalloys under wear conditions at high contact pressures and limited supply of lubricant have better performance compared to single-component iron, copper or aluminum coatings.

Pseudoalloys sprayed with composite wires have greater hardness compared to coatings of a similar composition sprayed with solid wires.

Therefore, they work better at high contact pressures in linear contact conditions. In cylindrical conjugations with a smaller value of contact pressures, coatings with a significant content of soft components, which are obtained by spraying solid wires, work in better and wear less.

Among the studied coatings sprayed with composite wires, iron-aluminum coatings are characterized by maximum wear resistance. However, they also have the greatest tendency to adhesion with the steel counterbody after stopping the supply of lubricant. Metallization coatings of the Cu-Al and Fe-Cu type are somewhat inferior to them in terms of wear resistance, but have a lower friction coefficient and a lower tendency to adhesion with a steel roller.

The performance of parts with a metallization coating largely depends not only on their tribotechnical characteristics, but also on the strength of adhesion of the coating to the surface of the product and the amount of internal stresses that arise in it during cooling.

The adhesion strength depends on the quality of preparation of the surface of the product for spraying, as well as modes and techniques of spraying the coating. But under other identical conditions, the adhesion strength will also depend on the thermophysical properties of the sprayed materials, the enthalpy of the particles, the possibility of exothermic reactions between the components of the sprayed materials.

Internal stresses, which depend on spraying modes and thermophysical properties of materials, when spraying coatings on the flat and internal surfaces of products, reduce the adhesion strength and contribute to the detachment of the coating from the surface of the part. When applying coatings to the outer surface of products, significant internal stresses can lead to the appearance of cracks and the destruction of the sprayed layer. Therefore, the adhesion strength and internal stresses significantly affect the performance of sprayed parts.

## Conclusions

1. The analysis showed that compared to cast anti-friction materials of a similar composition, anti-friction layers obtained by thermal metallization methods have 1.5–1.8 times higher wear resistance.

2. It has been proven that gas thermal coatings in the form of pseudoalloys, consisting of particles with different physicomechanical properties of materials, can have up to 2–3 times more wear resistance compared to single-component coatings made of materials included in the composition.

3. It is shown that in order to ensure a good fit of the contacting surfaces in the friction zone and particles of hard material with high wear resistance and resistance against sticking with the counterbody, anti-friction pseudoalloys of coatings should contain zones of particles of material with lower hardness to comply with the Charpy principle.

4. The positive role of aluminum as a soft component of anti-friction pseudoalloys, which at an affordable cost is well sprayed by the method of thermal metallization, has been experimentally confirmed.

5. It was determined that when spraying composite wires, for use as a solid component of anti-friction coatings, it is possible to use particles of alloying elements that form in the process of melting intermetallics or phase components of alloys that have a higher hardness.

6. Comparative analysis showed that two-component coatings sprayed with composite wires are characterized by higher hardness and wear resistance under conditions of high contact pressures compared to coatings of a similar composition sprayed with different types of solid wires.

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# ПІДВИЩЕННЯ ЗНОСОСТІЙКОСТІ ВАЖКОНАВАНТАЖЕНИХ ВУЗЛІВ ТЕРТЯ АНТИФРИКЦІЙНИХ ГАЗОТЕРМІЧНИХ ПОКРИТТІВ

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***Мета роботи.*** *Встановлення технологічних умов та параметрів для отримання матеріалів підвищення працездатності деталей машин в умовах важконавантажених вузлів тертя за рахунок квазітрибосистем газотермічних напилених антифрикційних шарів.*

***Методи дослідження.*** *Використано апріорні дані у комплексі з власними науковими розробками залежностей впливу хімічного складу газотермічних напилених антифрикційних шарів на фізико-механічні властивості поверхневого шару матеріалу, що руйнується в умовах трибосистем.*

***Отримані результати.*** *На основі проведених теоретико-практичних наукових досліджень одержано комплекс відповідних знань, які дозволяють визначити основні критеріальні вимоги для отримання антифрикційних шарів та графічно описати характеристики сплаву та показати кореляції параметрів між собою. Експериментально підтверджено позитивну роль алюмінію як м'якої складової антифрикційних псевдосплавів, який при*


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*доступній собівартості добре розпилюється методом термічної металізації. Доведено, що газотермічні покриття у вигляді псевдосплавів, що складаються з частинок, що володіють різними фізикомеханічними властивостями матеріалів, можуть мати до 2–3 разів більшу зносостійкість порівняно з однокомпонентними покриттями матеріалів, що входять до складу композиції.*

***Наукова новизна.*** *Наведено теоретико-практичні наукові дослідження з відтворенням системного аналізу для підвищення опірності до руйнування в умовах квазітрибосистем газотермічних напилених антифрикційних шарів. Показано, що для забезпечення доброго припрацювання контактуючих поверхонь у зоні тертя та частинок твердого матеріалу з високою зносостійкістю та стійкістю до злипання з контртілом антифрикційні псевдосплави покриттів повинні містити зони частинок матеріалу. з меншою твердістю для дотримання принципу Шарпі. Визначено, що при розпиленні композиційних дротів, для використання в якості твердої складової антифрикційних покриттів можливо використання часток легуючих елементів, що утворюють в процесі плавлення інтерметаліди або фазові складові сплавів, які мають більшу твердість. Порівняльний аналіз показав, що двокомпонентні покриття, напилені композитними дротами, відзначаються більш високою твердістю і зносостійкістю в умовах високих контактних тисків у порівнянні з покриттями аналогічного складу, напиленими різнотипними суцільними дротами.*

***Практичне значення.*** *Отримані результати дозволяють в рамках технічної та технологічної точності, яка необхідна в практичних інженерних прогнозах, визначити фізико-механічні властивості зносостійких напилених газотермічних антифрикційних шарів в умовах квазітрибосистем. Так, порівняно з відлитими антифрикційними матеріалами аналогічного складу антифрикційні шари, отримані методами термічної металізації, відзначаються в 1,5–1,8 рази більш високою зносостійкістю.*

***Ключові слова:*** *зносостійкість, твердість, квазітрибосистеми, антифрикційний шар, газотермічне покриття, напилення, псевдосплав.*


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