Evaluation of the possibility of using multilayer nanostructured coatings to improve the output characteristics of roller screw mechanisms

A V Zhdanov, E A Novikova, N S Dovbysh and A N Mitrofanov

Vladimir State University, Mechanical Engineering Technology Department, 87 Gorky Street, Russia

E-mail: zhdanov@vlsu.ru

Abstract. This article examines the effect of different coatings made of different materials on the efficiency of roller gears. Graphs of the dependences of the parameters of each coating are plotted. Tables of changes in the efficiency parameters and friction coefficients for the studied materials are given.

1. Introduction

Reducing the efficiency of gears due to friction is one of the most important problems in mechanical engineering. Various methods of solving this disadvantage are widely used. In particular, a change in the design of the actuator. In this paper, the analysis of changes in the value of the efficiency of RVM is carried out by applying nanostructured coatings to the working surfaces.

2. Experimental study of the properties of nanostructured coatings of roller screw mechanisms rollers

![Figure 1. Photos of roller samples with different types of coatings.](Image)
During the project, four types of nanostructured coatings for rollers were obtained (figure1, a-d):
- Coating 1: TiN/AlN;
- Coating 2: TiN/NbN;
- Coating 3: CrN/CNx;
- Coating 4: TiN.

Tribometrical parameters were taken in the following modes of operation on the CSM tribometer:
radius - 6.84 mm; ball radius – 5.5 mm; linear speed – 20 cm/s; normal load – 5 N, path – 500 m;
temperature – 25°C, humidity 60%, numerical results of scratch testing - in table 1[1].For all six types
of coatings, physical and mechanical properties were studied using a microcombitester and a CSM
tribometer, the research methods of which were developed at the 1-st stage of the project. The results of
measurements of the physical and mechanical properties of coatings are shown in table 1.

**Table 1. Results of measurements of physical, mechanical and tribological properties of
nanostructured coatings.**

| Coating   | H (GPa) | HV   | E (GPa) | H/E² | µ   | H (µm) |
|-----------|---------|------|---------|------|-----|--------|
| Coating 3 | 57      | 1239 | 319     | 1.84 | 0.5 | 2.0    |
| TiN/AlN   |         |      |         |      |     |        |
| Coating 4 | 54      | 2554 | 345     | 1.32 | 0.69| 3.05   |
| TiN/NbN   |         |      |         |      |     |        |
| Coating 5 | 43      | 2624 | 229     | 1.53 | 0.15| 2.5    |
| CrN/CNx   |         |      |         |      |     |        |

Figure 2 presents one of many coating photographs after scratch test, tribometrical and thickness
measurements [2].

**Figure 2.** Photographs of coating TiN / NbN after tests.
The roller screw mechanism (RSM) efficiency is calculated using the formula below [3]:

\[ \eta_{fm} \approx \frac{1}{1 + \frac{A_{sl,fr}}{(A_u + A_{roll,fr})/(A_u + A_{axial,fr})/A_u}} \] (1)

where \( A_u \) - useful work per turn of the screw, \( A_u = FS \);
\( A_{sl,fr} \) - work of sliding friction forces at non-pole coupling of threads per turn of the screw, at half the profile angle \( \alpha = \pi/4 \).

Useful work and the work of the friction forces can be found by the following proportion:

\[ \frac{A_{sl,fr}}{A_u} = \frac{2f}{1 - f'}, \] (2)

where \( f \) - coefficient of sliding friction separately for each coating;
\( A_{roll,fr} \) - losses on friction of the paired thread in the transfer:

\[ \frac{A_{roll,fr}}{A_u} = \mu \frac{2\pi}{s} (k + 1) \tan \alpha, \] (3)

where \( \mu \) - rolling friction coefficient (shoulder of the rolling friction moment);
\( A_{axial,fr} \) - friction loss of rolling bearings in the transmission.

The calculations involved both non-coated surfaces and clean steel surfaces. For the purity of the experiment, an additional variable was introduced in the form of plastic lubricants and the calculations measured the operation of the transmission both with and without it [4] (table 2).

| Steel             | Value of the \( f \) coefficient |
|-------------------|----------------------------------|
| Structural steel  | 0.56                             |
| Chrome steel      | 0.47                             |
| Tool steel        | 0.65                             |
| Stainless steel   | 0.45                             |
| Titanium alloy    | 0.58                             |

The values of the axial force and the thread stroke in the considered roller-screw transmission will be equal, respectively:

- \( F = 10\,000 \) N – axial force;
- \( S = 4 \) – the course of the thread.

Based on this, the value of useful work will be equal to: \( A_u = 40\,000 \) J = 40 kJ.

Using the proportion, we find the value of the work of the friction forces:

\[ \frac{x}{40} = \frac{2 \cdot 0.3}{1 - 0.3}; \]
\[ x = 34. \] (4)

Thus we get \( A_{sl,fr} = 34 \) kJ.

To determine the rolling friction in the mechanism [5], we need to know:

- Gear ratio \( k = 3 \);
- Angle of inclination of the thread turns \( \alpha = 45^\circ \);

Having the values of all the variables of the equation [6], we get the value of the rolling friction work, also taken for convenience as \( x \):

\[ \frac{x}{40} = 0.003 \cdot \frac{2 \cdot 3.14}{4} (3 + 1) \cdot \tan 45^\circ; \]
\[ A_{roll,fr} = 1.21 \text{ kJ}. \]
Now find the rolling friction [7] in the supports:
\[
\frac{x}{40} = \frac{1.21}{40};
\]
\[X = 1.21\] (6)

Now we have \(A_{axial fr} = 1.21\) kJ.
At this stage it is already possible to calculate the efficiency [8]:
\[
\eta_{fm} = \frac{1}{1 + \frac{34}{(40 + 1.21)}/(40 + 1.21)/40} \approx 0.54
\]
(7)

We get the value of the efficiency in the mechanism under dry and wet friction for structural steel in table 4 [9].

Table 3. The values of efficiency of steels under dry and wet friction.

| Steel            | Dry friction Value of efficiency | Wet friction Coefficient of friction |
|------------------|----------------------------------|--------------------------------------|
| Structural steel | 0.37                             | Structural steel                     | 0.59                                  |
| Chrome steel     | 0.48                             | Chrome steel                         | 0.5                                   |
| Tool steel       | 0.25                             | Tool steel                           | 0.6                                   |
| Stainless steel  | 0.31                             | Stainless steel                      | 0.48                                  |
| Titanium alloy   | 0.2                              | Titanium alloy                       | 0.55                                  |

After performing similar calculations using the obtained data, we have the following values in table 5:

Table 4. The values of efficiency of steels under dry friction.

| Steel             | Value of efficiency |
|-------------------|---------------------|
| Structural steel  | 0.52                |
| Chrome steel      | 0.42                |
| Tool steel        | 0.32                |
| Stainless steel   | 0.36                |
| Titanium alloy    | 0.25                |

Figure 3. Efficiency of coatings and steels with and without lubricant.
In the case of coatings, the same principles were used in finding the coefficients of friction as with steels, so for the sake of brevity, all the found values of coefficients and efficiency were entered in one General table and two graphs illustrated in figure 3. [10] It reflects the values of the friction coefficients for dry and liquid interaction of parts and the efficiency values corresponding to these coefficients in table 7.

The results of the conducted studies have shown that the use of nanostructured coatings in the operation of mechanisms affects a significant increase in the efficiency of these mechanisms. In particular, the CrN coating shows the best friction characteristics. A slightly less effective coating was based on titanium nitride. In the course of research, it was also found that the most effective steel for these purposes will be structural and chrome steel.

3. Conclusions
Improving the efficiency of mechanical gears due to nanostructured coatings is a poorly studied area, which allows for multiple experiments with both the composition of the applied substances and the materials of the working bodies of mechanisms. Such studies help to study this issue in more detail and form a general understanding of how a particular substance will behave in the workloads of mechanisms.

Acknowledgments
The work was carried out with the financial support of the state task of the Ministry of Science and Higher Education of the Russian Federation (agreement 075-03-2020-046/1, 17.03.2020, subject FZUN-2020-0015, state task of the VlSU GB-1187/20.

References
[1] Hebda M and Chichinadze V 1990 Handbook on tribology 1-3
[2] Kragelsky I V and Mikhin N M 1983 The friction units of machines Reference book p 320
[3] Kragelskii I V and Alisina I V 1978 Friction, wear and lubrication Handbook 2 p 400
[4] Berkovich I I and Gromakovskiy D G 2000 Tribology. Physical foundations, mechanics and technical applications Textbook for universities p 268
[5] Bagmutov V P, Savkin A N and Scab S N 2011 Wear parts of friction units of ground vehicles The textbook p 56
[6] Morozov V V, Kochetov D O, Dovbysh N S and Zhdanov A V 2019 Tribological properties of nanostructured coatings for roller screw mechanisms J. of Phys. Conf. Series 1331
[7] Morozov V V, Kosterin A B and Zhdanov A V 2018 Efficiency of Roller–Screw Mechanisms Rus. Engineer Res. 38 pp 263-267
[8] Bonanno A, Raimondo M and Pinelli M 2019 Use of Nanostructured Coating to Improve Heat Exchanger Efficiency Factories of the Future pp 275-292
[9] Bonanno A, Raimondo M and Zapperi S 2019 Surface nano-structured coating for improved performance of axial piston pumps Factories of the future pp 295-314
[10] Pastorello L, Bonanno A 2015 Application of Nano-structured coatings to heat transfer surface of heat exchangers The Fourteenth Scandinavian International Conference on Fluid Power, May 20-22, 2015, Tampere, Finland
[11] Malavasi Veronesi F, Caldarelli A et al 2016 Is a knowledge of surface topology and contact angles enough to define the drop impact outcome? Langmuir 6 pp 13