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# THE INFLUENCE OF SPECIFIC FEATURES OF LOAD AND HYDROGEN CHARGING ON STEEL TRIBOTECHNICAL PROPERTIES

**O. I. Balitskii,**[1,2,3] **V. O. Kolesnikov,**[1,4]
**L. M. Ivaskevych,**[1] **and M. R. Havrylyuk**[1]

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Wear resistance of structural steels 20 and 45 and high-nitrogen steel DDT68 during dry friction under different load conditions was studied. With an increase in slip to 20% at a load of 550 N the wear intensity increases 1.41 times for high-nitrogen steel and 1.54 times for structural steel. During sliding the surface fractures by tearing of the material under intense thermal setting, which affects the formation of secondary structures with increased oxygen concentration. With the reliability approximation of $R_2 = 0.87 - 0.99$ logarithmic and polynomial equations which describe the wear intensity in the conditions of slip and loading changes for the studied steels are obtained. After hydrogen charging the wear products have a significantly more complex textured microrelief with strips and larger sizes: $\geq 350$ μm ($P = 250$ N), $600 - 1000$ μm ($P = 400$ N), $800 - 1300$ μm ($P = 600$ N).

**Keywords:** dry friction, rolling friction, slip, high-nitrogen steel, structural steel, wear products, hydrogen charging.

## Introduction

Implementation and application of new tribotechnical materials is an actual scientific and technical task. Stainless steels, high-nitrogen steels with the increased physicomechanical properties ($\sigma_Y = 1000 - 1300$ MPa; $\sigma_U = 400 - 1000$ MPa; $K_{Ic} = 400$ MPa$\cdot$m$^{1/2}$) are among the perspective materials [1–3]. The scope of their application constantly expands. For example, steels with the addition of nitrogen are actively used to manufacture railway wheels, which work under dry rolling friction [4]. In such tribopairs complex fracture processes occur, which can be investigated by analyzing statistical information about defects and damages in surface layers, and the morphology of wear products [5–9]. Under the complex action of other factors (temperature, load, rate, lubrication conditions) hydrogen-containing environment significantly influences the operational and tribological properties [10–14].

The aim of the research is to investigate the tribotechnical properties of high-nitrogen steel in contact with structural steel during dry rolling friction under changes of conditions for loading, sliding and hydrogen charging.

[1] Karpenko Physicomechanical Institute, National Academy of Sciences of Ukraine, Lviv, Ukraine.
[2] West Pomeranian University of Technology, Szczecin, Poland.
[3] Corresponding author; e-mail: balitski@ipm.lviv.ua.
[4] Taras Shevchenko National University of Luhansk, Poltava, Ukraine.

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## Materials and Experimental Technique

Wear resistance was determined on an SMT-1 (2070) friction machine. The rotation frequency of the lower roller was 1480 rpm, and of the upper roller it decreased by 15% and 20%. The percentage of slip was calculated by the ratio of the rollers rotation rate. The load was 200–600 N under dry friction conditions. Before the experiments friction pairs were run-in (constant coefficient of friction is an indicator). Five experiments were performed for three points at different slip rates.

The lower roller (∅ 42 mm) was made of steel 45 (hardness HRC 55–60, microstructure – martensite) or steel 20 (HRC 35–40, ferrite-pearlite). The upper roller (∅ 35 mm) was made of high-nitrogen DDT68 steel with hardness HRC 45–50. An austenitic metal matrix with microhardness of 4.2–5.0 GPa was registed in DDT68 steel microstructure. The chemical composition of the materials is given in the Table.

**TableChemical Composition of Steels (wt.%)**

| Steel grade | C | Si | Mn | Cr | Ni | Mo | V | N |
|---|---|---|---|---|---|---|---|---|
| steel 20* | 0.21 | 0.33 | 0.37 | 0.11 | 0.14 | – | – | – |
| steel 45** | 0.47 | 0.21 | 0.75 | 0.24 | 0.25 | – | – | – |
| steel DDT68 | 0.06 | 0.52 | 19.4 | 17.5 | 0.13 | 2.08 | 0.14 | 0.97 |

[*] 0.04 S, 0.034 P, 0.12 Cu, 0.05 As;
[**] 0.02 S, 0.022 P, 0.24 Cu, 0.07 As.

The microstructure and friction surface parameters were examined using an EVO-40XVP electron microscope with an INCA Energy 350 microanalysis system at the Center for Electron Microscopy and X-ray Microanalysis in Karpenko Physico-Mechanical Institute of the National Academy of Sciences of Ukraine. X-ray structural analysis was carried out on the DRON-2 installation. The TOUP VIEW 3.7 software complex was used to determine the phase composition of steels microstructure, the size of wear products, damage on friction surfaces, and 3D reconstruction of wear surfaces.

The hydrogen influence on friction was studied on samples of high-nitrogen steel, previously hydrogen-charged in a 26% solution of sulfuric acid with 5 mg/l arsenic oxide catalyst for the current strength of $0.5\ \text{A/cm}^2$.

## Results and Discussion

Comparative experiments under dry friction with changes of rolling rates (Fig. 1), when hardness and structural-phase composition of contacting bodies are important, were performed [8, 9, 15–19]. The intensity of wear increases as follows: martensitic steel 45 (HRC 55–60), high-nitrogen DDT68 steel (HRC 45–50), steel 20 with ferrite-pearlite microstructure (HRC 35–40). The intensity of wear for steel 20 under load of $600\ \text{N}$ was $1.38\ \text{g}/1000\ \text{m path}$, and for DDT68 steel the intensity of wear was $0.2\ \text{g}/1000\ \text{m path}$. The lower roller of ferritic steel 20 (body) was worn significantly more than DDT68 high-nitrogen austenitic steel roller (counterbody). The intensity of wear for steel 45 (body) at a load of 600 N was 0.11 g / 1000 m path , and for steel DDT68 (counterbody) it was 0.4 g / 1000 m path . The change in the metal matrix type (from ferritic to martensitic) and an increase in hardness (from 35 to 60 HRC) led to the change in the intensity of wear for contact pairs. The regression equation of the wear intensity dependence on the applied load was obtained. For friction pair steel 20–DDT68 steel $I_{st\,20} = 0.1296P^2 - 0.4779P + 0.4511$, $R^2 = 0.9755$; $I_{stDDT68} = 0.016N^2 - 0.0547N + 0.0761$, $R^2 = 0.9873$. For friction pair steel 45–DDT68 steel $I_{st\,45} = 0.1299N^2 - 0.0959N + 0.1211$, $R^2 = 0.9912$; $I_{stDDT68} = 0.0104N^2 - 0.0402N + 0.0406$, $R^2 = 0.9241$.

Hydrogen charging of rollers significantly influenced friction and wear under loads over 200 N. The intensity of wear for hydrogen charged roller made of steel DDT68 increased significantly more than 5 times, and under load of 600 N wear intensity increases almost 10 times. The roller without hydrogen charging (Fig. 2) wears more intensively (in 1.6–2.5 times), which indicates the probable release of hydrogen in the contact area and the embrittlement of martensitic steel.

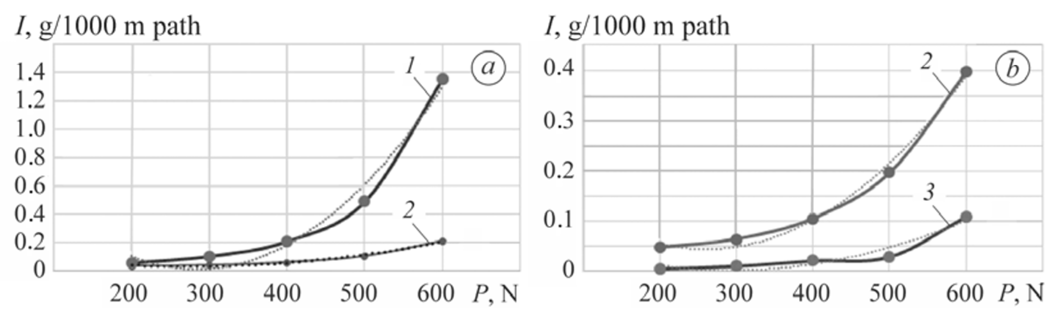


**Fig. 1.** Dependence of wear intensity for friction pairs under dry friction on the load $V = 2.25$ m/s: (a) steel 20 (1)–steel DDT 68 (2) pair; (b) steel 45 (3)–DDT68 steel (2) pair.

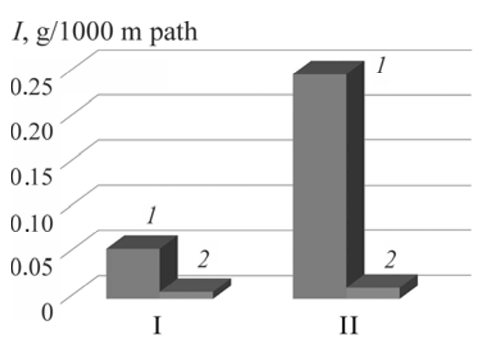


**Fig. 2.** Generalization of researches of DDT68 steel roller under dry friction (I) without hydrogen charging and (II) with hydrogen charging in pair with (1) DDT68 steel, (2) steel 45; $P = 250$ N; $V = 2.25$ m/s.

The average intensity of wear of the studied steels under a load of 550 N increases with the slip increases; it can be described by the equations as follows: $I_{st\,45} = 0.0034 \ln S + 0.115$, $R^2 = 0.9023$; $I_{st\,DDT68} = 0.0255 \ln S + 0.1143$, $R^2 = 0.87$ (Fig. 3a). The friction coefficient of rollers remains almost stable, and sound emission is absent when slip equals 15%. When slip equals 20% a large number of places with material cohesion and tearing were observed on areas of the friction surfaces, which in some experiments was accompanied by sound emission. The number of defects and damages on roller surfaces increases with the increase of slip (Fig. 3b), which is characteristic of many materials of friction pairs [1, 3, 5–7, 12–15]. In researches of the wheel-rail steels pair under sliding rolling, it was established that in the range of 240–300 HV, depending on slip, there can be three types of wear, which differ in the rate, the type of surfaces, and the morphology of the wear products wear [15–19]. The regularity that a steel with higher hardness (and martensitic microstructure) is less worn than a steel with lower hardness and cold-deformed austenite, was also confirmed [15, 16]. Quite possible that as a result of pressure treatment, the alloy no longer had "reserves" for self-strengthening under friction. The wear intensity of steel 45 rollers under 20% slip is 1.54 times higher, and for high-nitrogen steel DDT68 rollers wear intensity is 1.41 times higher than the wear intensity without slip. It confirms the influence of strength characteristics conditioned by high-nitrogen steel structure.

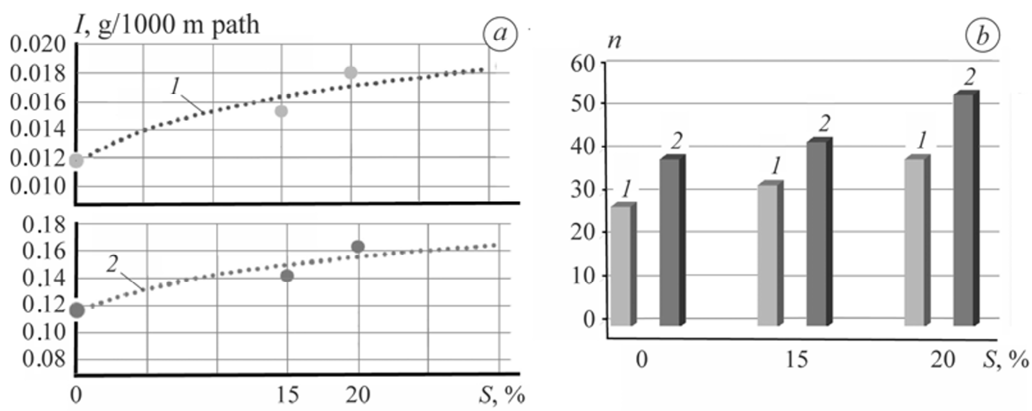


**Fig. 3.** Dependence of average wear intensity of studied steels under dry friction for load 550 N on (a) slip; (b) diagram of distribution of the number of different size defects on the rolling surface for slip changes: (1) steel 45, (2) DDT68 steel.

For both steels oxygen was recorded on the fracture surfaces during 20% slip (Fig. 4). The amount of oxygen directly in the defect zone of steel 45 (Fig. 5, zone I) was 4.27 mass% (12.79 at.%); no oxygen was recorded on the surface plane (spectrum 2). For DDT 68 steel oxygen is present in the fracture zone in the place of "material tearing" under thermal seizure (Fig. 4c, spectrum 3) in the amount of 19.65 mass% (43.58 at.%) and on the surface without fracture (Fig. 4d, spectrum 4) oxygen is present in the amount of 7.08 mass% (16.84 at.%). The higher content of oxygen on the surface of high-nitrogen steel confirms its presence in the composition of passivating films of insoluble oxides.

Oxygen directly in the dimple of the defect zone indicates that during fracture (tearing) the conditions are formed to form the oxide, which influences secondary structures and, as a result, the intensity of fracture processes. High-nitrogen steels have special absorption properties of the surface, where a protective layer of graphite particles remains for a long time [7]. This leads to the minimization of wear during friction [7, 15, 18]. On the friction surface in the tearing zones, there is an increased content of Cr and Mo carbide-forming elements, which indicates the intensive fracture of the material in the zone of their increased concentration [6]. When slip increases the fracture intensifies, the time of surfaces contact decreases, the number of damages increases, and the passivating film, which can reduce the intensity of wear, recovers faster.

Under load $P = 400$ N the size of wear products grows from 30–50 μm, 50–70 μm to 60–90 μm under 0%, 15% and 20% slip, accordingly. The shape of wear products changes from flat ("petal-like" [1, 3]) to a more three-dimensional shape (Fig. 5).

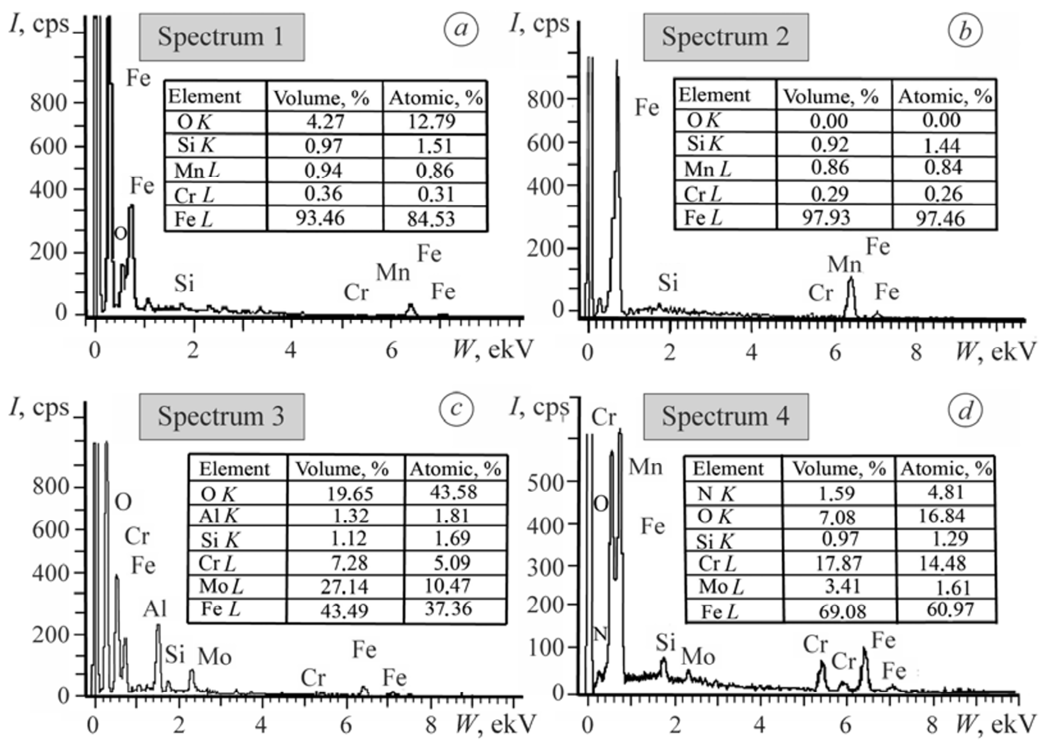


**Fig. 4.** Spectra (with energy dispersion) of characteristic X-ray radiation of surface elements of (a, b) steel 45 and (c, d) DDT68 steel.

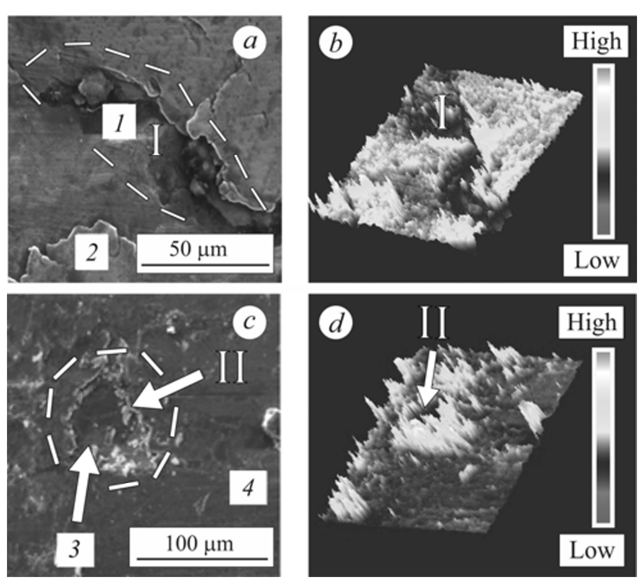


**Fig. 5.** Damaged friction surface of (a) steel 45 and (c) DDT68 steel; their 3D reconstruction (b, d) with areas I and II, respectively; $P = 250$ N; $V = 2.25$ m/s.

Hydrogen charging significantly changes the morphology of wear products (Fig. 6). In the initial state their medium size was 25–100 μm under load of 500 N and 15–40 μm under load 250 N, but wear products of the smaller size, of several microns, were also found. After hydrogen charging among the wear products were those which dimensions were $> 350$ μm ($P = 250$ N), $600 - 1000$ μm ($P = 400$ N), $800 - 1300$ μm ($P = 600$ N).

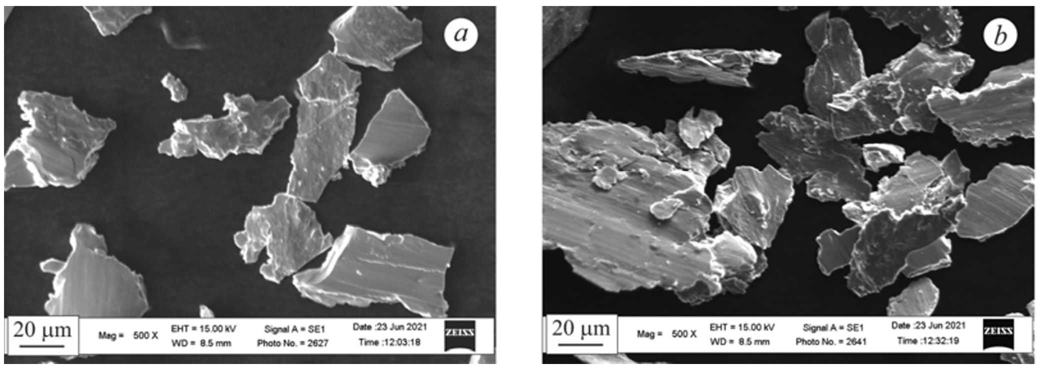


**Fig. 6.** Wear particles of high-nitrogen DDT68 steel ($P$ = 500 N; $V$ = 2.25 m/s), formed under dry friction: (a) steel without hydrogen charging, (b) after hydrogen charging.

Hydrogen charging and load increase the lead to the appearance of more three-dimensional shape particles. There are bands on the surface of the wear products (Fig. 6a), but on the charged samples the bands are more clear and the surface is more textured (Fig. 6b). During the study of electrolytically hydrogen-charged samples, the so-called Lüders bands were recorded [1, 3]. On a microscale hydrogen promotes plasticization at the stage of plastic deformation, and embrittlement at the stage of quick crack opening [10–13, 20–26]. Hydrogen easily diffuses and reacts both on the surface and in the depth of the metal. As the crack propagates deep into the alloy, increasing stresses act in those microvolumes in which microplastic deformation occures in the Lüders band. As a result of dislocation activity increase at the crack tip caused by the presence of diffusion mobile hydrogen, the surface of the band is a stress concentrator significantly stronger than the initial concentrator [21, 27–29]. The influence of hydrogen is the greatest at the crack tip, where the entry is facilitated by sliding, and hydrogen local concentration increases [8, 30–32]. The wear of hydrogen charged steels is several times more intense under dry rolling friction. It occurs due to the saturation of surface layers with hydrogen, which contributes to the intensification of fracture processes.

The obtained results can be used to develop a catalog that will systematize the relationship between the surface morphology and the conditions for the formation of wear products. The obtained logarithmic and polynomial equations that describe the intensity of wear will make it possible to predict the serviceability and durability of tribocouples, including those that undergo hydrogen charging.

## CONCLUSION

It was established that under the load of 600 N in the contact pair of steel 20 and DDT68 steel the intensity of wear was 1.38 and 0.2 g/1000 m path, for pair steel 45 and steel DDT68 0.11 and 0.4 g/1000 m path, respectively. Therefore, a high-nitrogen austenitic steel is worn 6.9 times less than ferritic steel (HRC 35) and 3.6 times more than a hardened martensitic steel (HRC 60) during dry friction. With an increase in sliding from 0 to 20%, the intensity of roller wear increases, in particular, under the load of 550 N it increases in 1.41

(high-nitrogen DDT68 steel) and 1.54 times (structural steel 45). After 20% slip, the thermal seizure nuclei are fixed on the friction surfaces, and inside them the oxides, being a part of passivating films, are recorded. The average size of wear products increases from 30–50μm to 60–90 μm at 0, 15 and 20% slips, respectively.

Hydrogen charging of one of the rollers led to an increase in its wear up to 10 times with simultaneous increase in the wear intensity of a roller without hydrogen charging in 2 times. After hydrogen charging wear products have a more complex microrelief and significantly larger sizes: 350 μm ($P$ = 250 N), 600–1000 μm ($P$ = 400 N) and 800–1300 μm ($P$ = 600 N).

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***Колесніков Валерій Олександрович*** – к.т.н., доцент кафедри технологій виробництва і професійної освіти ДЗ «Луганський національний університет імені Тараса Шевченка», м. Полтава, науковий співробітник відділу «Міцності матеріалів і конструкцій у водневовмісних середовищах», Фізико-механічного інституту ім. Г.В. Карпенка НАН України, м. Львів, http://orcid.org/0000-0003-2010-3368, e-mail: kolesnikov197612@gmai.com.

**Колесников Валерий Александрович**

***Kolesnikov Valerii*** – PhD (Eng), Associate Professor of Department of Production Technology and Professional Education Luhansk Taras Shevchenko National University, the City of Starobilsk, Ukraine, researcher of the Department of strength of materials and structures in hydrogen-containing environments

Karpenko Physico-Mechanical institute of the NAS of Ukraine http://orcid.org/0000-0003-2010-3368, e-mail: kolesnikov197612@gmai.com.

https://www.scopus.com/authid/detail.uri?authorId=8918120300

https://orcid.org/0000-0003-2010-3368

https://www.researchgate.net/profile/Valerii-Kolesnikov

http://dspace.luguniv.edu.ua/jspui/