The potential of application of Ni-layer for enhancement of utility properties of freight wagons

Z Andrsova\textsuperscript{1a}, P Kejzlar\textsuperscript{1b}, T Bakalova\textsuperscript{1c}, M Petru\textsuperscript{1d}, P Podzimek\textsuperscript{2}

\textsuperscript{1a}\textsuperscript{,b,c,d}\footnote{Technical University od Liberec, Studentska 1402/2, 461 17 Liberec 1} \textsuperscript{2}\footnote{Funchem s.r.o., Vratislavicka 59/14, 460 06 Liberec 6}
\textsuperscript{1a}zuzana.andrsova1@tul.cz, \textsuperscript{1b}pavel.kejzlar@tul.cz, \textsuperscript{1c}totka.bakalova@rul.cz, \textsuperscript{1d}michal.petru@tul.cz, \textsuperscript{2}podzimek@funchem.cz

Abstract The construction of 4-axled freight wagons used for transportation of bulk materials is limited with respect of minimal angle allowing emptying the bulk cargo and limited lifetime caused by abrasion caused by intensive wear between the wagon wall and transported cargo. A potential of application of protective chemically-deposited Ni-layer was evaluated based on tribological testing.

1 Introduction

For the mass transportation of bulk materials are mostly used freight wagons, it is a profitable and environmentally friendly model of transportation. However, as in other sectors, there is an increasing emphasis on further cost reductions. Although the railway sector is very conservative, manufacturers of rail vehicles are trying to offer wagons with reduced weight (eg replacement of conventional steel parts with composite elements, often with built-in smart electronics), increased capacity or longer lasting (operational life of the railway wagon may be up to 30 years). Freight wagons (Figure 1) are limited in their construction by the angle of the walls, which is necessary to empty the load. In addition, the discharge flap under the vehicle wall is heavily loaded to wear and its lifetime is several times lower than the whole vehicle. In cooperation with the manufacturer of freight wagons, the surface treatment of flaps with chemical nickel coating was tested. The coating is intended to increase wear resistance, corrosion resistance and sliding properties which allows to modify the construction of the wagon to increase the capacity and extend the lifetime of the flap. [1]

The surface treatment with chemical (electroless) nickel was chosen because of its suitable physical-mechanical properties, but also for ease of application compared to electroplated coatings with comparable parameters. While in electroplating we encounter many limitations resulting from the laws of electrolysis (especially difficult plating of cavities, uneven distribution of layer thicknesses, necessity of using anodes etc.), in the case of chemical deposition, a coating is formed on the surface simply by chemical reduction from the plating bath which is heated to the specified temperature. In the case of chemical nickel plating, in addition to Ni, also elemental phosphorus is deposited in the coating. The resulting Ni\textsubscript{3}P alloys are characterized mainly by high abrasion resistance, corrosion resistance, and uniform thickness of the deposited coating. The overall resulting properties of the coating are influenced by the phosphorus content according to which the coatings are divided into three groups – with low content (1-4 wt\% P, 675 HV, corrosion resistance of 24 h due to ISO9227),
with medium content (5-9 wt.% P, 575 HV, corrosion resistance of 200 h due to ISO9227) and with high content (10-12 wt.% P, 525 HV, corrosion resistance of 1000 h due to ISO9227). The Ni₃P layers can also be created with the addition of admixtures which further improve their properties (e.g., Al₂O₃, SiC, PTFE, graphite etc.), or they can create more complex alloys with B, Co, W etc. Properties of Ni₃P coatings may be further enhanced by heat treatment, when the phosphorus distribution changes and the porosity of the coating is reduced. At the same time, the brittleness is reduced, the hardness is increased and the adhesion is improved by creating a diffusion layer. Usually the heat treatment, so-called hardening of the coatings is performed in the range of temperatures from 200°C (with the dwell in the tens of hours) up to 400°C (with the dwell in hours). If the coatings are cured at the upper limit of the temperature range, they achieve hardnesses up to 1000 HV. The chemical and corrosion resistance of Ni₃P coatings depends primarily on the layer thickness – with the increase in thickness decreases the number of open pores which are completely closed at thicknesses above 30 microns. The mentioned resistance also depends on the phosphorus content.

The paper assesses the suitability of chemical Ni application on discharge flaps mainly from the viewpoint of tribological properties - the coefficient of friction and wear rate. Rotational tribology according to ASTM G99-95 “Ball-on-disc” was used to determine these indicators. Its principle consists in placing the non-rotating ball on the surface of the sample (in the shape of a disc). At a certain distance from the center of the sample is placed a "Ball" loaded with a predefined force. The table together with the disc is rotated at a defined speed (rpm), and performs a predetermined number of rotations or a certain path length. The result of the measurement is the dependence of the coefficient of friction on the path length. [5-7]

In addition to tribological properties, the microhardness of the deposited layers and the effect of welding on the layer were verified – wagons are conventionally welded by fusion welds and due to the anticipated thermal degradation of the layer at the weld site, the replacement of the weld by bonded joints is considered.

![Figure 1. Illustration image if the freight wagon, green highlighted discharge flaps to which surface treatment has been applied.](image)

2 Experimental

2.1 Sample preparation, deposition of layers

For the purposes of testing, two types of samples were prepared from rolled steel sheets S235JR with a thickness of 5 mm, which are used to produce discharge flaps. The sheets were stripped with a phosphoric acid prior to plating to remove the oxide layer. Due to the fact that it is intended to be applied to 6x2 m sheets, in terms of technical possibilities, the surface treatment towards lower initial surface roughness has not been considered yet, therefore, even the specimens were not ground or polished prior
to deposition, the initial surface roughness was around Ra 12.5. Three groups of samples were prepared for tribology and hardness measurement (labelled A,B,C, see Figure 2) with circular shape and diameter of 30 mm. Group A was untreated, groups B and C were coated with chemical Ni. Group C was further hardened in an electric induction furnace for 4 hours at 300 °C. Two groups of samples were prepared for the analysis of welded joints (labelling D, E, see Figure 2) with rectangular shape and size 40x200 mm. Both groups were coated with chemical Ni, group E was further hardened in an electric induction furnace for 4 hours at 300 °C. The reverse side of the specimens was protected against nickel plating by a barrier to assess the effect of the coating on welding. Samples were subsequently joined by a lap weld joint. Commercially available solutions were used to deposit coatings on all samples (Coventya Enova EF9B and Enova AM100, 5-9% P, 85-90°C/ 40 min., layer thickness of 20 μm).

![Figure 2](image-url)

**Figure 2.** Preview of test samples for tribological testing (A, B, C) and for weld analysis (D, E).

### 2.2 Experimental methods

Rotational ball-on-disc tribology according to ASTM G99-95 was used to evaluate the coefficient of friction. As a counterpart in the friction pair was used ceramic ball of Si₃N₄, resp. Al₂O₃. The choice of the counterpart is based on empirically determined information about the transported materials, which cause the most wear on the flap surface when emptying. The selected ball materials should be as close as possible to their properties. The measurement and evaluation of the coefficient of friction between the samples and the ceramic ball was performed on a tribometer CETR UMT Multi-Specimen Test System. The wear of the disc material from the friction pair was evaluated by mechanical profilometer Dektak XT. The microhardness of layers HVₙₐ was measured using microhardness tester Zwick 3212 under the load of 1 N for 10 s, using Vickers indenter. Ten indentations were performed on each sample and the mean microhardness was calculated. On nickel-plated surfaces (corresponding to the flap supporting structure) were welded to the nickel-plated sides of the samples under standard parameters (arc fusion welding). Samples after welding were evaluated visually and a macroscopic examination of the welds was also performed – metallographic samples were prepared and macroscopic and microscopic images were taken. Also detailed samples of the metal layers at the weld site and in the heat affected zone were taken on the same samples.

### 3 Results and discussion

The aim of the performed experiments was to evaluate the coefficient of friction and comparison of friction properties using different prepared surfaces, as well as to evaluate the degree of wear of the sample after tribology. It can be seen that the coefficient of friction (Table 1) does not change much on contact with the Si₃N₄ ball – as can be seen, for example, from the wear test of the samples (Figure 3), particles shredded from the surface fall between the sample and the counterpart thereby the coefficient of friction increases again. This is is probably due to the roughness of the sample surface. When the surface comes into contact with the Al₂O₃ ball, the friction coefficient of the nickel-plated surface reduces up to 50%. The ball has a higher hardness and there is no crumbling of the particles that can cause an increase in the coefficient of friction. The results of the tribological specimen wear evaluation (Table 2) show that as the coating hardens, wear decreases. Significant is the reduction of wear, especially in hardened surfaces, in case of Si₃N₄ it’s up to 95 %, in case of Al₂O₃ ball even 97 % against the initial state (according to the volume of material removed - wear rate). Microhardness measurements show an increase of Ni₃P coating hardness about 30% after heat treatment (see Table 3). The microscopic
analysis of the weld showed that the presence of the layer does not affect the quality of the weld – undesirable changes were not evident in the weld microstructure. However, welding will significantly damage the layer at the weld site, in the heat affected zone is then significantly impeded in its integrity (Figure 4). This means that welding of already coated sheets is not permitted – the corrosion resistance of the entire weldment would be fundamentally impaired.

Table 1. Average values of the coefficient of friction [-].

| Surface          | Base material | Ni – non-hardened | Ni – hardened |
|------------------|---------------|-------------------|---------------|
| counterpart Si₃N₄ | 0.857±0.133   | 0.838±0.234       | 0.705±0.208   |
| counterpart Al₂O₃| 0.828±0.167   | 0.427±0.251       | 0.307±0.202   |

Figure 3. Wear of sample surface after tribology against the ball Si₃N₄: a) initial state, b) non-hardened coating c) hardened coating. LOM, BF, magn. 25x.

Table 2. Measured values of specimen wear after tribology using counterpart Si₃N₄ and Al₂O₃.

| Surface          | Base material | Ni – non-hardened | Ni – hardened |
|------------------|---------------|-------------------|---------------|
| Profile width [µm] | 1016.9        | 499.79            | 425.72        |
| Profile depth [µm] | 6.734         | 2.827             | 0.921         |
| Volume of material removed per unit length of profile [µm³] | 6697.8        | 1233.21           | 292.08        |
| counterpart Al₂O₃ | 966.6         | 434.2             | 212.03        |
| Profile depth [µm] | 4.645         | 1.845             | 0.523         |
| Volume of material removed per unit length of profile [µm³] | 4310.85       | 621.09            | 101.32        |

Table 3. Measured values of microhardness of layers HV₀.1.

| Sample        | Microhardness HV₀.1 [-] |
|---------------|-------------------------|
| non-hardened  | 594  598  595  594  602  596  592  595  590  598  595 |
| hardened      | 920  923  925  988  924  927  920  921  925  923  924 |
4 Conclusion

The results show high potential of application of chemically deposited Ni₃P layers. The samples show an increase in wear resistance of 81-97% against the base material, the upper limit is in the case of heat treatment of the layer (supported by an increase in hardness of about 30%). At the same time, the sliding properties can also be improved by reducing the coefficient of friction when comparing the results of the coated samples with the base material, without pretreating the surface roughness. However, this is conditioned by the characteristics of the counterpart (in practice, a material of lower hardness tends to seize into the substrate) – it would be necessary to achieve a significant reduction in the surface roughness of the surfaces to be coated. The increase of the sliding properties is significant especially when using Al₂O₃ ball, where the coefficient of friction decreased by up to 50%. A significant increase in the lifetime of the discharge flaps can be expected and, due to the achieved coefficient of friction, the possibility of modifying the structure to increase the vehicle capacity. From the analysis of the layers in the area of the weld joints is obvious the need for replacement of the standard fusion weld joint with a joint without thermal interference, eg by bonding, which will require further application development due to the continuous dynamic loading of the joints and the required vehicle service life. Surface pretreatment to reduce surface roughness is possible for parts of this size when using mechanical surface grinding and polishing, but it could cause undesirable increases in production costs and the efficiency of the treatment would have to be considered.

Based on the results of laboratory testing, a pair of flap plates without mechanical pretreatment were experimentally plated (see Figure 5), fixed to the structure of the flap by bonded joint (Letoxit LH 21) and subjected to trial operation of freight wagon that is to verify the properties of the layer in real conditions. In the case of a favorable response, the innovation of the construction of the freight wagon due to higher capacity will be considered (adjustment of discharge angle). The development of the glued joint will be initiated and NSS 480 corrosion tests and, for example, PV1200 shock tests should also be part of the application development of bonded joint technology. At the same time, the corrosion resistance of Ni₃P layer is assumed to be tested for the purpose of this unconventional application.
Figure 5. Application of Ni:P coating on 6x2m discharge plaps.

Acknowledgements
The result was obtained through the financial support of the Ministry of Education, Youth and Sports of the Czech Republic and the European Union (European Structural and Investment Funds - Operational Programme Research, Development and Education) in the frames of the project “Modular platform for autonomous chassis of specialized electric vehicles for freight and equipment transportation”, Reg. No. CZ.02.1.01/0.0/0.0/16_025/0007293.

References
[1] M Pazcek et al 2016 A concept of technology for freight wagons modernization IOP Conf. Ser.: Mater. Sci. Eng. 161 012107
[2] P Golias et al 2010 Electroless nickel plating Techpark o.z.: Tribotechnika 1338-0524
[3] A W Goldenstein, W Rostoker, F Schlossberger and G Gutzeit 1957 Structure of chemically deposited nickel J. Electrochem. Soc. 104(2): 104-110
[4] A H Graham, R W Lindsay and H J Read 1965 Structural changes in heated electroless Ni/P alloys. J. Electrochem. Soc. 112(4): 401-413
[5] D Jakubeczyova et al 2015 Tribological tests of modern coatings J. Electrochem. Soc. 10): 7803-7810
[6] P J Blau 2008 Friction Science and Technology: From Concepts to Applications (New York: CRC Press) ISBN 9781420054040 pp 132-174
[7] Bhushan, B. (2002) Introduction to Tribology (New York: John Wiley & Sons, Inc.) pp 23 - 188