Evaluation of Coating Material Structure of Screw Type Compressor Rotor Contact Surfaces

G. Muiznieks, E. Gerins, A. Katasevs, J. Ozolins, and G. Pikurs

***Abstract*—In engineering, as well as in other manufacturing industries, the use of compressed air is an important catch. Compressor production and service company Fonons, Ltd often deals with damage of screw type compressors, sometimes even irreversible. Damages that draw up to 15% are linked to strong wear out of compressor friction knot (rotors). This, in effect, reduces the optimum productivity and work efficiency of the compressor, increases losses between rotors. Compressor service time diminishes.**

Work foundation is the analysis of methods how to improve screw rotor surfaces. It is necessary as one of the concluding treatment operations in the manufacturing process. It may reduce the influence of the abrasive elements on the contact surface, diminish wear intensity, and increase the service time.

Improved contact surface of rotors, which are coated with TiN coating by using physical vapour deposition (PVD) technology, is analysed within the framework. Surface quality control is executed with modern methods, including surface 3D topography analysis and coating quality estimation with the atomic force microscopy (AFM). The main materials are analysed characterizing parameters change according to the recommendation for manufacturing wear proof coatings.

***Index Terms*—wear, surface topography, atomic force microscopy, quality, and wear intensity.**

I. Introduction

Nowadays, the demand for compressed air is still growing in all kinds of industries in Europe including Latvia. The most extended range in compressor industry is for oil flooded screw type compressors, which are technologically most fashionable, efficient, safe, and wear proof. Generally, compressors are mechanical devices for increasing inflowing air pressure or energy transmission. Efficiency, wide range of speeds, pressure differences, compact design, low cost, rapid growth and a variety of other qualities allow the possibility for wide use in various technological processes. The basic parts in screw type compressor design are two specially created revolved, parallel placed rotors (Fig.1.). The pressure increases between those two rotors [1].

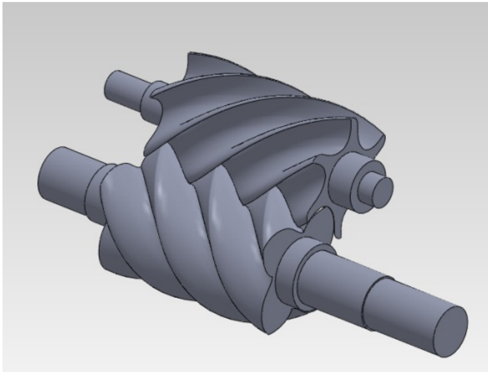

Fig.1. Rotors of screw type compressors

During the exploitation time, the main active parts of oil flooded screw type compressors (Fig.1.) are subordinated to a wide range of speeds, pressure differences, changeable cyclic loads, and various working environments. The result of variable working circumstances can cause damage, which can be even irreversible. One of the most common compressor airend failures is the wear out of the main friction knot-faulty rotor profile of the compressor. That reduces the optimum productivity of compressors, increases leakage between pressures channels, as well as reduces its operational efficiency. Certain viscosity oils are used for reducing friction and wear intensity. There is an opinion that while the oil flows between the rotors, they do not wear out. However, the experience of Fonons Service Company, Ltd. has shown that it is not enough to turn off the detrimental effect of the abrasive particles on the rotor contact surfaces. It is necessary to create a contact surface of the rotor which would allow them to work in extreme conditions.

The excessive wear out of rotor contact surface is the beginning of the problem chain. The most common cause of screw compressor airend damage is the abrasive particles. Abrasive damages appear if various abrasive particles penetrate between rotors or if something goes wrong with oil injection and atomization between the rotors. Thereby a partial or direct contact between rotors appears, causing an intensive wear of rotors. The interruption of oil supply becomes the general cause of damaged rotors and other completing compressor parts.

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Herewith, there is a necessity to increase wear resistance of compressor rotor contact surface against mechanical damages. Together with rotor contact surface improvements we could restore wear out joints. The main task of rotor profile restore is to get the initial parameters of the damaged surface. Before surface coating for low level (0.5…10µm) wear of rotor profile, it is necessary to execute the mechanical surface treatment that in result liquidates wearing tracks, forming the correct profile geometrical form of rotors. In case of high level (10…1000µm) wear a new contact surface should be build up with a new melted material layer which prevents wearing. The result of the mechanical treatment is the use of profiling tools, necessary compatible sizes and surface quality.

Rotor wear intensity (I_h) is a function which depends on a number of factors: material hardness (HV), plasticity (A), maximal endurance (Rm), surface topographies (Ra; Sm_1; Sm_2; Sa) and a couple of less relevant factors. Nowadays, the industry has many different technologies for the improvement of surface mechanical properties. There is a constant increase in the number of cases where the latest technologies are used and superior and wear resistant layers have been applied on airend helical lobe rotors. New coated and restored rotors have much higher mechanical properties than uncoated ones. The major technological processes of coatings are melting, sputtering, deposition [2], [3]. The effectiveness of coating is characterized by the rotor wear resistance and overall economic efficiency of airend. Different coating materials are available nowadays. Materials may be homogeneous or heterogeneous.

The foundation of this work gives an analysis of the surface quality of the rotor contact area, which was subordinated to processing. Sample rotor contact surface was coated with nano structured TiN layer, which was taken on a surface by using PVD technology, cathode arc deposition, and a thin coating was obtained. The TiN coating was deposited at the nano coating laboratory of Riga Technical University. The purpose of the coated layer is to increase the hardness of rotor contact surfaces, to improve surface quality, and to reduce wear intensity, thus obtaining a longer service time of the airend. High hardness and wear proof homogeneous material was coated on an explored test piece.

II. Research Part

A. Review Stage

The oil flooded screw type compressor CE55RW rotors are used in the case research. The results of the chemical analysis of the rotor material are represented in Table 1. The chemical characterization agrees with steel C35. The physical characteristics of material are represented in Table 2.

TABLE I
Results of Chemical Analysis

Fe	C	Si	Mn	P	S
98.2	0.358	0.231	0.673	<0.0050	0.0146

Cr	Mo	Ni	Al	Co	Cu
0.0958	0.0154	0.115	0.0141	0.0110	0.230

Pb	Nb	Ti	V	W	Zr
<0.010	<0.0030	0.0170	0.0036	0.0250	<0.003

The explored material samples were coated with nano structured TiN coating. TiN coatings have much better mechanical properties than basic material - higher hardness of the surface layer, resistance to wear and lower friction losses. That kind of layers is widely used in protecting coatings to protect products against aggressive environments and strengthen the contact surfaces of friction, as well as increase the product lifetime.

TABLE II
Primary Characterizing Parameters of Rotors Contact Surface

Parameters	Value
HV	127-173
R_m	430N/mm^2
R_e	215N/mm^2
Sa	0.413µm
Sz	5.17µm
R_{a1}	0.287µm
R_{a2}	0.404µm
RS_{m1}	0.0378mm
RS_{m2}	0.0446mm
Friction coefficient µ	0.159

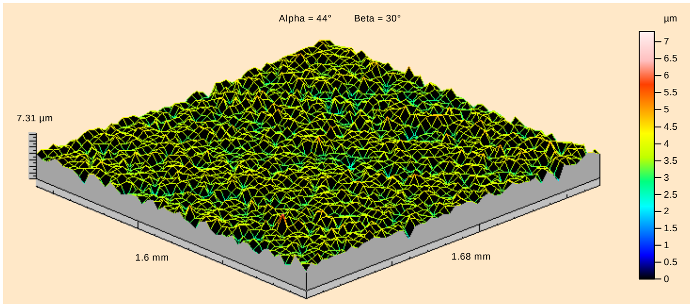

Fig.2. Surface 3D topography before coating

Titanium nitride is used in various industries for achieving higher wear resistance of wearing knots. However, screw compressor manufacturers are not using any coatings for oil flooded screw compressor rotors. TiN is used also as a top-layer coating, usually with nickel (Ni) or chromium (Cr). TiN is non-toxic and may also be used in medicine. For obtaining thin layer coating of such material, the physical vapor deposition methods (sputter deposition, cathode arc deposition or electron beam heating) [2] were used. High Young's modulus of TiN allows making thin coatings. TiN coating has significantly higher melting temperature (2930°C) in comparison with the carbon construction steel substrate (1400…1500°C). This allows screw rotor operation under heavy working conditions. Another quality of TiN is the low thermal expansion. The thermal regime of compressor fails frequently and occurs in dry contact operating cases.

Physical vapor deposition technology allows forming functional property of coating material in the level of separate atoms and molecules [3]. The obtained coating in a vacuum allows extracting metal without admixtures and contaminations. Physical Vapor Deposition technology has many advantages:

- spacious speed range of coating;
- regular coated layer;
- coated layer with certain thickness;
- availability to form the crystalline structure of the coated layer.

The nature of the particle stream during the deposition technology depends on the particle type, energy and chemical activity, as well as on the substrate material.

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One of the most important processes in coating technology is surface preparation. Binding force of the coating material and the sample detail depends on the quality of the surface layer. To increase the adhesion nature of the materials, we can form it with understratum layer ≤0.1mm of metal or their alloys (molybdenum, nickel, aluminium, titan and other) that promote the formation of hard chemical connection with the basic material. Substrate temperature is one of the most important parameters that govern the film microstructure. Substrate temperature controls the composition, structure and morphology of the film by affecting the adatom mobility on the substrate, as well as the rate of any chemical reaction occurring on the substrate [4].

The surfaces of rotor contact, which will be inferior to coating, get cleaned from dirt, subordinate to tooling. On the surface the necessary topography is created, which affects the binding of the sputtering material and wear resistance of the rotor contact surface.

Before inserting the rotors in a vacuum chamber, they were degreased with a detergent. After fastening the air was pumped until the pressure level equalling $P = 6.7 \cdot 10^{-3}$Pa. In order to increase the surface cleanness of the rotor contact surface, the vacuum chamber was used for the treatment with ion flow for about 3 minutes. Ion treatment removed upper layers where the most surface defects were. At the same time, it activated the overhead stratified surface, and chemical connections tore. After the surface treatment, the rotors were heated up for better binding of the materials. Afterwards the rotor contact surface coating was carried out through preparing operations accordingly to the case coating parameters: $P_N=3 \cdot 10^{-3}$Pa; $U_p=140$V; $I_I=80$A; $V_{ar}=3 \cdot 10^{-3}$Pa; t=20min. For equalizing the resulting stresses in the coating layer, the rotors were cooled in a vacuum chamber for 10 minutes.

B. Final Stage

In order to verify the quality of the coated surface, the analysis of the surface topography was executed by using Taylor Hobson Form Talysurf Intra 50 and Talymap Expert software. Due to TiN coating on the contact surface of the compressors rotors, the main attention was paid to the influence of the parameters on rotor wear resistance and wear intensity.

TABLE III
CHARACTERIZING PARAMETERS OF ROTORS CONTACT SURFACE AFTER COATING

Parameters	Value
HV	713
Sa	0.439 µm
Sz	6.04 µm
R_{a1}	0.258 µm
R_{a2}	0.314 µm
RS_{m1}	0.058 mm
RS_{m2}	0.0708 mm
Layer thickness, h	2.85 µm
Coefficient of friction µ	0.213

TiN layer coated on surface gives certain characterizing parameters (Table 3). The obtained data displays that the surface layers have clearly visible repeated increase in hardness HV and reduced parameter values of surface topography Sa, Ra, Sm. In this sample case, friction µ was increased. Examining the surface 3D topography image (Fig.4.), we can deduce that thin (h=2.85µm) coating does not smooth out processing tracks of the surface and unevenly placed outgrowths (0.15…0.3µm) appear on the surface. These growths appear during PVD processing. For better understanding of the surface forms and the character of ledges, rotor contact surfaces were exposed to the analysis of surface quality that was executed by the atomic force microscopy.

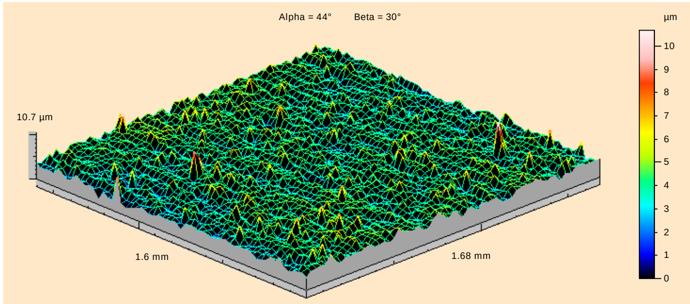
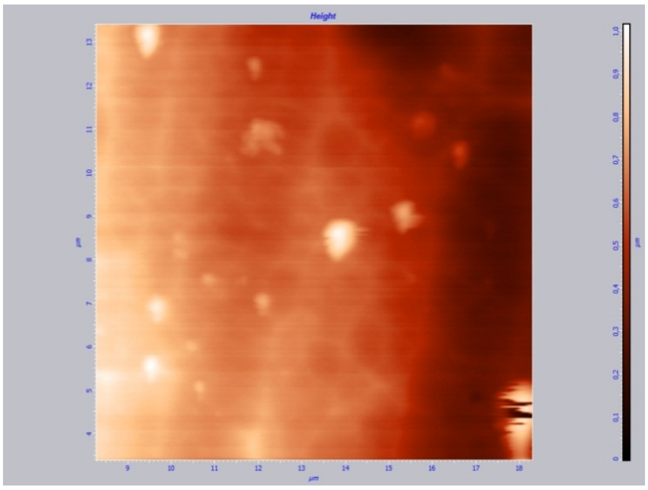


Fig.4. Surface 3D topography after coating

The analysis of the surface topography with AFM was performed in a nano level where we can estimate the surface topography much deeper. Solver P47–PRO AFM with NT–MDTNova information processing program was used for scanning. The scanning was executed in several modes: contact, noncontact and in the mode of force modulation using CSG, NSG, and FMG type probes. Examining the surfaces by AFM (Fig.6) showed uneven surface that had already been testified by the analysis of surface 3D topography. On the surface, higher and lower ledges of different forms were found (Fig.7. a) ranging from 140…330nm, as well as cavities (Fig.7. b).



a) AFM output surface in the mode of contact

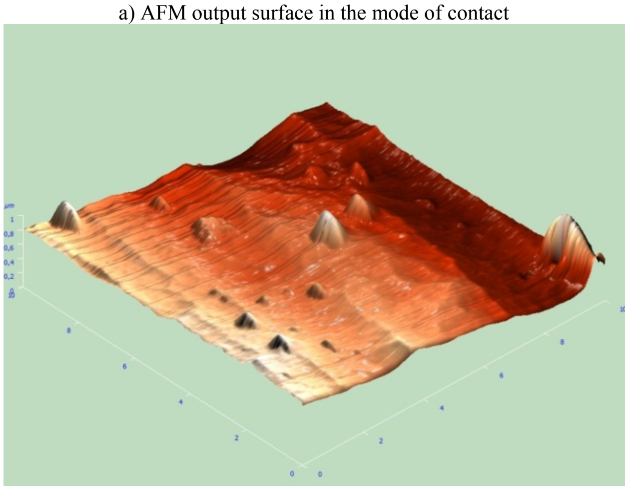

b) AFM 3D topography

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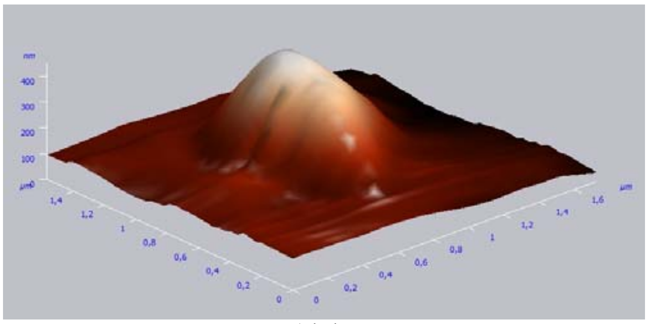
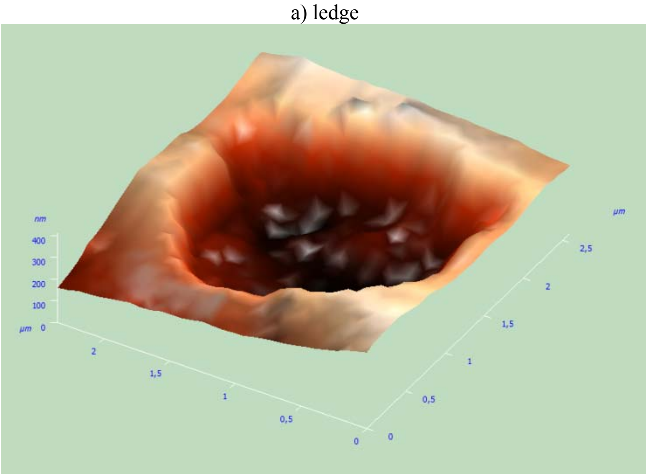
Fig.6. Assessment of surface quality with AFM

The forms of ledges have a diamond shape, whereas cavities – circular shape. These ledges create the porosity of coating. These are the microdroplets of titanium. The microdroplets appear when the cathode arc method in the environment of vacuum is used. Such amount of microdroplets in the investigated coating resulted from the low temperature of the substrate during the deposition that could not alloy the coating material. The substrate temperature also has a significant influence on the coating microstructure and its adhesion; the influence increases with the rise of the temperature [5], [6]. The mechanical processing of this layer may produce the detachment microdroplets.



a) ledge



b) cavity
Fig.7. Defects of surface

For the flattening of microdroplets and improving the coating quality, it is necessary to flux the surface. The characterizing parameters of the surface topography by AFM scanning are represented in Table 4.

TABLE IV
PARAMETERS OF SURFACE TOPOGRAPHY BY AFM

Parameters	Value
Max	1012.48 nm
Min	0 nm
Peak-to-peak, Sy	1012.48 nm
Ten point height, Sz	522.168 nm
Average	575.366 nm
Average Roughness, Sa	147.876 nm
Second moment	602.21
Root Mean Square, Sq	177.797 nm
Surface skewness, Ssk	-0.208807
Coefficient of kurtosis, Ska	-0.901124
Entropy	13.1801
Redundance	-0.320351

AFM scanned surface displays that the obtained coating does not smooth out processing tracks but saves the form of the previous surface. In the final stage, the coated TiN rotor contact surfaces were put under mechanical revision, after the mathematical conformity to the law of profiling which was performed beforehand. That reduced the time of wear-in for communicating surfaces and eliminated the defects formed on the surface.

TABLE V
CHARACTERIZING PARAMETERS FOR THE SURFACE AFTER TREATMENT

Parameters	Value
HV	713
Sa	0.392µm
Sz	4.3µm
Thickness, h	2.80µm
Coefficient of friction µ	0.192

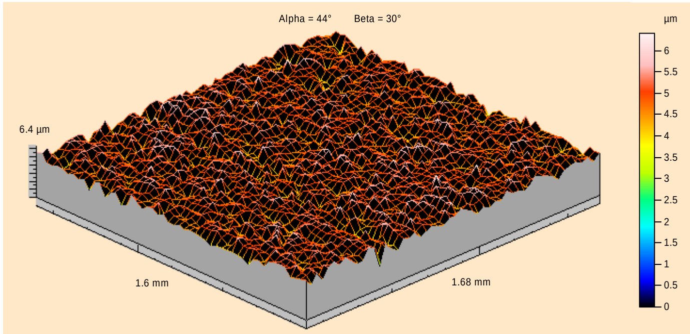


Fig.8. Surface after treatment

After the final machining of rotor contact surface we have a surface with improved surface parameters (Table 3.) of topography and reduced coefficient of friction µ=0.192 (before treatment µ=0.213). In the 3D image (Fig. 8.) the surface is represented after treatment displaying the surface without any ledges and cavities.

Based on the results on efficiency loss caused by rotor friction, Zaytsev [7] suggests that the coefficient of friction must be limited by a value of 0.2. He proposes Eq. (1) to calculate the maximum allowed specific wear rate of the coated surface

$$\zeta = \frac{h}{w_c} \cdot \frac{v_{ci}}{v} \cdot \frac{2\pi}{\omega_i t}, \qquad (1)$$

where h is the allowed wear depth; w_c is the linear contact load; v_{ci} is the contact point velocity relative to the surface of the rotor i; v is the relative rotor velocity (slip velocity) at the contact point; ω is the angular speed of rotor i; t is the compressor operation time. [8]

The wear intensity for elastic contact may be calculated by the relation:

$$I_h = \left(\frac{CRa}{S_{m1}}\right)^{ty+1} \cdot \left(\frac{K\mu_1 f}{\sigma_0 \theta}\right)^{ty} \cdot F_3(\gamma)\frac{Ac}{Aa}, \qquad (2)$$

where

$$F_3 = \left(\left(4 \cdot (2\pi)^{1/2} \cdot f \cdot (1+\mu_1)\right)/\sigma_0 \cdot \theta_1\right)^{ty} \cdot \left(\frac{A_c}{A_a}\right);$$

$C = S_{m1}/S_{m2}$, whereS_{m1}, S_{m2} are the average step of surface imperfections across and along the friction direction; Ra is the average height of surface imperfections; μ is Poisson's coefficient; f is the friction coefficient; ty is the index of fatigue curve; Aa, Ac – the nominal and outline contact square, θ – the ductility constant referred to materials of

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machine parts in friction pair; σ_o is the ultimate stress characterizing the standard (average) mechanical properties of the body; K – the index which depends on the Poisson's coefficient and friction coefficient values.

Using wear intensity the theoretical relationships (1) and (2) of friction theory have been established saying that forming coated contact surface of screw type compressor with the above mentioned characterizing surface parameters (Table 3.) extend rotor lifetime at least for 3…5%.

III. Conclusion

The following research results are presented with several suggestions:

- such a technology for forming coatings is creating a porous coating. For improving coatings it is necessary to flux surface or finish tooling;
- thin coatings 0.5…10μm can be used for liquidation of limited wearing tracks;
- careful surface preparation is necessary for high-quality coating extraction;
- liquidation of processing tracks owes to form coatings which >2.8μm;
- thin coatings 0.5…10μm are effective if they are delivered on a harder substrate.

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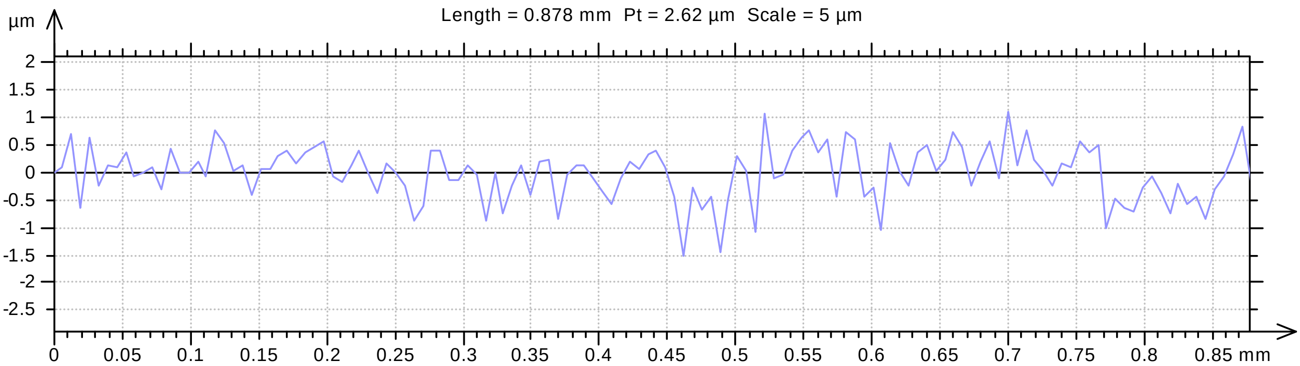

Fig.3. Profile diagram of the surface before coating

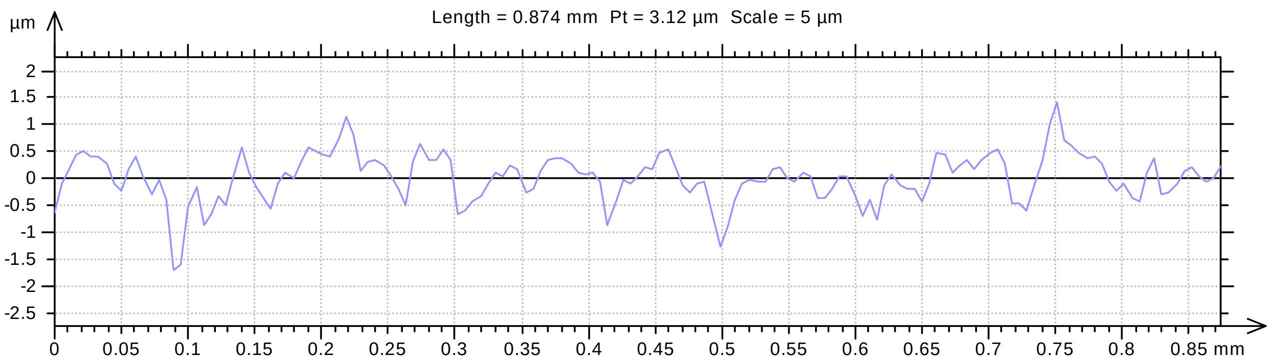

Fig.5. Surface profile diagram after coating

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