RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
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"Apparatus engineering" field

RESEARCH ON THE INCREASE OF WEAR RESISTANCE OF CONTACT SURFACES OF SCREW TYPE COMPRESSOR ROTORS

Sector: Science of machines

Subsector "Manufacturing engineering"

Summary of Doctorate Thesis

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DOCTORATE PAPER
NOMINATED FOR GRANTING DOCTOR'S DEGREE IN ENGINEERING SCIENCES
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The Doctorate paper to receive the degree of engineering doctor will be presented in public on ………………… 2013 at the Faculty of Transport and Mechanical Engineering of Riga Technical University, 6k Ezermalas street, lecture room 405.

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CONFIRMATION

I hereby confirm that I have developed the present Doctorate paper that has been submitted to the Riga Technical University for receiving Doctor's degree in engineering. The Doctorate paper has not been submitted to any other university for receiving scientific degree.

Gatis Muižnieks …………………… (Signature)

Date: ……………………

The Doctorate paper has been made in the Latvian language and consists of Introduction, five chapters, work conclusions, appendix, list of used information sources, summary, 97 figures, 35 tables, constituting altogether 123 pages. The list of used information sources includes 74 titles.

CONTENT

GENERAL CHARACTERISTICS OF DOCTORATE PAPER

Urgency of topic

More and more often modern equipment not only in engineering industry but in any other manufacturing sector is working by compressed air. Thus application of compressed air generally plays an important role. With the growth of production capacities technologically more modern, more economic and safer compressor equipment is being used more and more often – including oil flooded screw compressors.

As a result of a long-term cooperation with the compressor producer SIA "Fonons" in Latvia, manufacturing and servicing oil flooded screw compressors of company GHH in the Baltic States, shortcomings in compressor designs were detected causing failures of compressor operation. These failures are encountered in compressors operating in improper working environment. Provided these compressors are used according to their specifications operation of equipment is faultless. However in real life everything is quite different. Statistical data collected during the long-term work of the company "Fonons" show that 15% of users disregard service conditions resulting in different compressor operation failures, sometimes even irreversible. The most often encountered compressor failure is wear of friction point (rotor), as well as reduction of compressor productivity, increase of leakages, which in its turn reduce the operation efficiency.

Such problems are urgent also in other sectors of industry in the operation of similar equipment. Thus a solution should be found for the prevention of these operation failures. At present there are some few researches showing a possibility to increase the service life of rotor contact surfaces. *The intensified wear of rotor contact surfaces is a starting point of problem chain and therefore the present doctorate paper is aimed at the investigation of a possibility to reduce the rotor contact surface wear*. The researches, which were aimed at the improvement of physical and mechanical properties of the material present technological solutions related to the vacuum deposition of coatings. For the improvement of contact surfaces' properties of different friction pairs and also as a protective coating in other industrial sectors, for instance tool manufacturing, coatings are being used, including titanium nitride (TiN).

Very few information is gathered on the compressor rotors profile, versions for the restoration of defined productivity and maintenance possibilities, because the abrasive substances - the polluted air, wear products, service conditions – rather considerably affect the rotor service life. This aspect would be very essential for those users operating screw compressors under harsh operation conditions.

In the compressor production sector there are no researches about the wear of contact surfaces of oil flooded screw type rotors and its reduction solutions using TiN. Thus experiments and calculations must be made for the efficiency evaluation of such coatings on the oil flooded rotor contact surfaces, provide informative material both to manufacturers and their representatives dealing with compressor servicing and maintenance. For these reasons the paper can be regarded as pressing.

Work objective

The objective of the present work is: to increase wear resistance of asymmetric rotors of oil flooded screw type compressors.

Work tasks

The following tasks are carried out to reach the set objective:

1. Analyses of screw type compressor design and rotor working surface;
2. Investigation of oil flooded screw type compressor failures and rotor wear;
3. Mathematic modelling of geometrical forms of rotor and processing tools;

4. Technological solutions for the increase of wear resistance of rotor contact surfaces;

5. Development of criteria for the assessment of efficiency of technological processes of contact surfaces treatment.

Research methods

To reach the objective of the Doctorate paper and the set out tasks the quantitative research method – mathematical statistics – was used. For a valuable experimental part the following equipment was used: metallurgical microscope *IM 7000*, roughness indicators *Tesa – rugosurf 10, Talysurf Intra 50,* spectrometer *WAS PMI-MASTER PRO,* dynamic meter of mechanical properties of company *EQUOTIP,* toolmaker's microscope *MMN-2*, microhardness meter *ПМТ-3,* equipment for friction measurement designed and produced by the author, atomic force microscope *Solver P47-PRO,* a.o.. To solve the tasks and represent the results graphically the following software was used: *SolidWorks*, *Microsoft Visio,* supplement *Gauss Jordan* of *Quinn-Curtis* to the scientific and engineering equipment *Turbo Pascal*, *Microsoft Excel, Rugosoft 10-10G, NT-MDT Nova, Talymap Expert, ScopeImage Advance,* a.o..

Scientific novelty

The scientific novelty of the Doctorate paper is as follows:

1. Application of mono-layer TiN wear resistant coatings in the restoration, improvement and manufacturing of contact surfaces of oil flooded screw type compressor rotors.

2. Researches on the wear reduction of contact surfaces of oil flooded screw type compressor rotors considering surfaces 3D properties.

Research results

1. Mathematic expression for designing and production of contact surfaces of screw rotors and shaping cutting edges of cutting tools.

2. Criteria for substantiation of choice of material for screw type compressor rotors.

3. Experimental covering of surfaces of screw type compressor rotors with wear resistant TiN coating and analyses of their physical and mechanic properties.

4. Two criteria based methods of assessment of efficiency improvement of rotor contact surfaces' treatment technology:

4.1. Criterion based on the contact type of rotor surface;

4.2. Criterion considering the wear process.

Practical application

Application of basic approaches to the choice of material in the development of screw type rotors, as well as components of other mechanisms.

Applied methods in the development of mathematical expressions for describing surfaces in theoretical modelling of compressor rotors, tool profile, as well as other working surfaces.

The developed contact surfaces' improvement assessment criteria can be used both in the prediction of changes of contact type and also changes of wear size. It should be noted that these developed criteria can be applied not only for the assessment of improvement efficiency of treatment of rotor contact surfaces' coating but also for different other treatment technologies related to the study of wear process.

In this paper author defends

1. Application of wear resistant TiN coatings, their evaluation and recommendations for the improvement of mechanical properties of oil flooded compressor rotor contact surfaces.

2. Criteria for the assessment of improvement efficiency of rotor contact surfaces' treatment.

Paper approbation

The reports on main conclusions and results of the Doctorate paper have been delivered at the following conferences and seminars:

Thesis and reports

1. Muižnieks G., Geriņš Ē. „Skrūves kompresoru mezglu konstrukciju pētījumi”. RTU 48. Starptautiskā Zinātniskā konference, Rīga, Latvija, 2007, 12. oktobris.
2. Muižnieks G., Geriņš Ē., Zvirgzds J. „Skrūves tipa kompresoru rotoru izgatavošanas tehnoloģiju analīze”. Latvijas Universitātes 24. zinātniskā konference, veltīta LU CFI 30 gadu jubilejai, 2008.g. 20.-22. februāris, 63 lpp.
3. Muižnieks G., Geriņš Ē., Zvirgzds J. „Materiāla izvēles nosacījumi skrūves tipa kompresoru rotoru izgatavošanai”. Latvijas Universitātes 24. zinātniskā konference, veltīta LU CFI 30 gadu jubilejai, 2008.g. 20.-22. februāris, 64 lpp.
4. Muiznieks G., Gerins E. “Conditions of Materials Choice in Manufacturing of Pressure Originated Details”. Proceedings of 4th International Conference Mechatronic Systems and Materials, July 14–27, 2008, Bialystok, Poland, p. 127.
5. Muižnieks G., Geriņš Ē. „Skrūves tipa kompresoru rotoru virsmas fizikāli mehānisko īpašību uzlabošanas metožu analīze”. RTU 49. Starptautiskā Zinātniskā konference Rīga, Latvija, 2008, 12. oktobris.
6. Muižnieks G., Geriņš Ē. „Šķidruma plūsmas rotorsūkņu rotoru virsmas fizikāli mehānisko īpašību uzlabošanas metožu analīze”. Latvijas Universitātes 25. zinātniskās konference, veltīta doc. Ludviga Jansona simtgadei 2009.g. 11.-13. februāris, 25 lpp.
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8. Muižnieks G., Geriņš Ē. „Skrūves tipa rotoru kontakta virsmu mehānisko īpašību uzlabošanas iespējas izmantojot nano pārklājumus”. RTU 51. Starptautiskā Zinātniskā konference Rīga, Latvija, 2010, 14. oktobris.
9. Muižnieks G., „Titāna nitrīta pārklājumi”. Seminārs ar komersantiem projekta „Mehānisku elementu virsmas un to iekšējās struktūras nanotehnoloģiskie pētījumi mašīnbūvē” īstenošanas jautājumos „Materiālu virsmu jaunākie pētījumi” RTU Būvniecības fakultāte, Rīga, Āzenes 16/20-213, 2011. gada, 19. maijs.
10. Muižnieks G., Ozoliņš J. „Nanostruktūras pētījumi ar atomspēka mikroskopa palīdzību”. Seminārs ar valsts zinātniskajām institūcijām projekta „Mehānisku elementu virsmas un to iekšējās struktūras nanotehnoloģiskie pētījumi mašīnbūvē” īstenošanas jautājumos „Mašīnzinātnes sasniegumi nanotehnoloģijās” Latvijas Brīvo arodbiedrību savienības namā, Bruņinieku 29/31 Rīga. 2011. gada, 29. septembris.
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12. Muižnieks G., Ozoliņš J. „Atomspēku mikroskopa izmantošana virsmas pētījumos”. Seminārs ar komersantiem projekta „Mehānisku elementu virsmas un to iekšējās struktūras nanotehnoloģiskie pētījumi mašīnbūvē” īstenošanas jautājumos „Nanotehnoloģija un virsmas mehānika” RTU Būvniecības fakultāte, Rīga, Āzenes 16/20-213, 2012. gada, 15. maijs.
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1. Muiznieks G., Gerins E. “Specific characters of design on screw type compressors”. Proceedings of 6th International Scientific Conference, Engineering for rural development, May 24-25, 2007, Jelgava, Latvia, p. 216-220.
2. Muiznieks G., Gerins E. “Usability of analytical methods in design of instrument profile of screw type compressors”. Proceedings of 7th International Scientific Conference, Engineering for rural development, May 29-30, 2008, Jelgava, Latvia, p. 229-235.
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6. Muižnieks G., Geriņš Ē. “Materiālu izvēles nosacījumi mūsdienu mašīnu un aparātu būvē”. RTU Zinātniskie raksti, Mašīnzinātne un transports, Jubilejas krājums 6. Sērija, 31. Sējums, RTU, Rīga, 2009, 56-61 lpp.
7. Rudzitis J., Krizbergs J., Oditis I., Torims T., Kumermanis M., Muiznieks G., Strazdina I. “Determination of 3D surface roughness parameters by using cross-section methods”. RTU Zinātniskie raksti, Mašīnzinātne un transports, Jubilejas krājums 6. Sērija, 31. Sējums, RTU, Rīga, 2009, 71-74 lpp.
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Scope of Doctorate paper and structure description

The Doctorate paper has been developed in the Latvian language and consists of Introduction, five chapters, work conclusions, appendix, list of used information sources, summary, 97 figures, 35 tables, constituting altogether 123 pages. The list of used information sources includes 74 titles.

CONTENT OF DOCTORATE PAPER

INTRODUCTION

In today's dynamic machine building era when different design machines and apparatuses are being developed, as well as integrated industrial mechanization and automation, close attention is being focused on the production of high quality products. High work efficiency, high rotor rotation speed, processes within high pressure range, compactness, and low expenses of production, rapid growth and design diversity allow wide use of screw type compressors in different technological processes. More and more often volumes of used compressed air are growing in any production process. Technologically more advanced, economic, safer and more wear resistant compressor machines are being looked for, for instance, screw type compressors. Compressor machines are closely related to any production sector in Latvia. Use of screw type compressors in different branches of industry is widely spread, since they have started to replace traditional piston type compressors. Screw type compressors demonstrate many advantages, however still there are numerous factors affecting their functioning, which must be investigated, and rational conclusions should be found, and designs, which must be perfected to attain a more efficient compressor operation.

In compressor operation different operation failures are encountered that are even irreversible. The most often encountered compressor failures are wearing of main components – friction joints, and drop of productivity. The present Doctorate work is dealing with the research of possibilities to restore the defined productivity of the oil flooded screw type compressor and extend the service life of asymmetric rotor profile. Modern achievements allow looking for technological solutions for manufacturing of main compressor spare parts.

For successful completion of work the oil flooded screw type compressor asymmetric rotors produced by German company GHH RAND were being used and studied. Researches on these rotors were carried out in cooperation with the compressor producer in Latvia, SIA "Fonons" and Riga Technical University.

Chapter 1. ANALYSES OF SCREW TYPE COMPRESSOR DESIGN AND ROTOR WORKING SURFACES

As a result of a long-term cooperation with the compressor producer SIA "Fonons" in Latvia, manufacturing and servicing oil flow screw type compressors of company GHH in the Baltic States, shortcomings in compressor designs causing failures of compressor operation were detected. These failures are encountered in compressors operating in improper working environment. Statistical data collected during the long-term work of the company "Fonons" show that 15% of users disregard service conditions resulting in different compressor operation failures. The most often encountered compressor failure is wear of friction point (rotor), as well as reduction of designed compressor productivity, increase of leakages, which in its turn reduces the operation efficiency. Such problems are urgent also in other sectors of industry in the operation of similar equipment. Thus a solution should be found for the prevention of these operation failures. At present there are some few researches showing a possibility to increase the service life of rotor contact surfaces. *The intensified wear of rotor contact surfaces is a starting point of problem chain and therefore the present doctorate paper is aimed at the investigation of a possibility to reduce the rotor contact surface wear*. The researches aimed at the improvement of physical mechanical properties of the material present technological solutions related to the vacuum deposition of coatings. For the improvement of contact surfaces' properties of different friction pairs and also as a protective coating in other branches of industry, for instance tool manufacturing, coatings are being used, for example titanium nitride (TiN) coating.

1.1. Compressors and their application

A short insight is presented in the development of screw type compressors. At the present industrial development stage one of the most popular air compressors are screw type compressor machines, which are closely connected with any manufacturing branch in Latvia. Screw type compressors are simple design rotor positive displacement rotary machines, which can operate at high rotation speed, under wide pressure ranges and high air flow volume with high efficiency. Besides they are safe and compact. They can operate with different working fluids, which can be both gas and dry vapour, or different mixtures, changes of whose phases take place in the compressor [22]. Thanks to their small size and high productivity they are being used in different sectors of national economy and production.

1.2. Specific character and advantages of screw type compressor design

Screw type compressors are simple design rotor positive displacement rotary machines. In screw type compressors air supply is similar to that in piston compressors making forth and back movements but with higher air supply frequency [8]. In the Doctorate paper big attention is paid to oil flooded screw type compressors. The peculiarities of their design are being analysed, as well as insight given into their operation principle. The chapter analyses advantages of oil flooded compressors over other types of compressors [8, 14, 31].

1.3. Compressor rotor contact surfaces and current researches

This chapter deals with specific characteristics of main compressor components and requirements to their efficient operation. The main screw ty11pe compressor components are rotors shaped with particular screw profile – driving and driven. The development of screw type compressors is connected with the perfection of rotor production technology. Efficient compressor operation requires a rotor profile where internal air flow in the compressor would be maximum, short sealing line, at the same time air leakage and internal friction related to relative motion between contact surfaces would be smaller. Larger air flow and smaller leakages increase the compressor volume efficiency [24, 25]. Thanks to modern workbenches the rotor manufacturing time has fallen from several hours to minutes and production precision has increased [4]. As a result rotors with smaller tolerances can be produced, thus reducing internal air leakages to minimum, allowing to reduce dimensions by changing screw compressor efficiency which is higher than in other type compressors [21].

Nowadays scientists have devoted their researches to the influence of temperature and thermodynamics on rotor deformations, using for their analyses finite element method [7, 20]. Dependence of pressure and flow changes on rotor turning angle is investigated [6]. 3D modelling is carried out – for the evaluation of compressor operation efficiency [12, 13, 15], profiling of compressor rotors [19]. Similarly there are analysed and introduced alterations in compressor design and rotor profiles, improving parameters of their operation [10, 17, 18, 22, 23], a.o.. In other sectors of machine industry one can find researches related to the investigation of compatibility wear of different elements (flat, cylindrical surface).

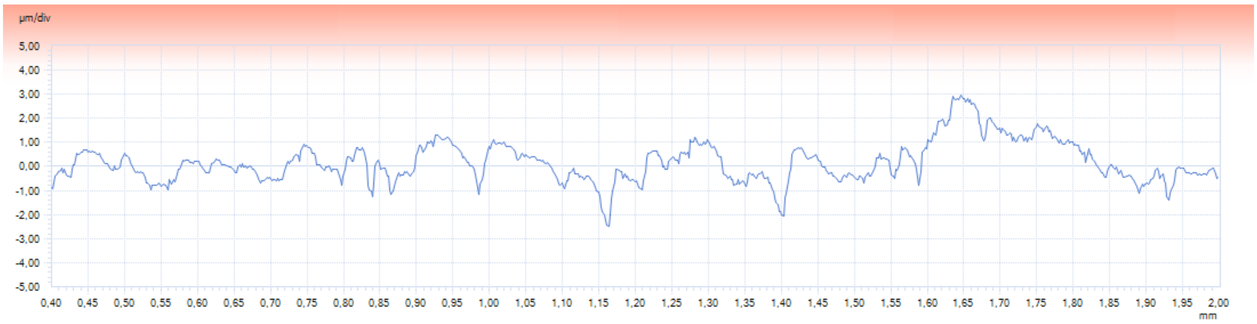
Very few information is gathered about the versions of restoration and preservation possibilities of compressor rotor profiles, specified productivity. In compressor manufacturing field there are no researches on oil flooded screw type rotor contact surface wear and their reduction solutions using monolayer TiN coatings. Therefore it is necessary to make experiments and calculations for the evaluation of such coatings' efficiency on contact surfaces of oil flooded rotors, provide informative material both to manufacturers and their representatives dealing with compressor servicing and repair work.

Chapter 2. ANALYSES OF SCREW TYPE COMPRESSOR OPERATION FAILURES

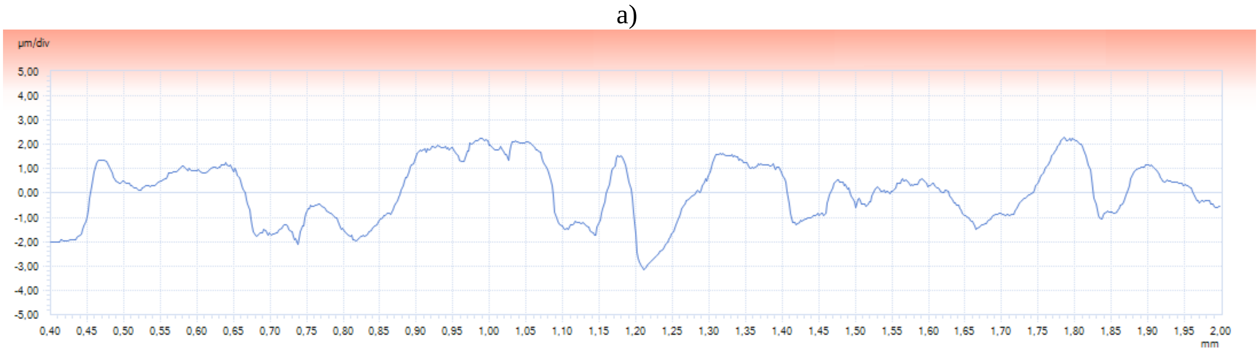
This chapter analyses the types of main compressor damages based on the statistical data of company "Fonons", and systematises them. During the oil flooded screw type compressor operation together with air oil is pumped in or injected, which prevents direct rotor contact. As soon as oil supply between rotors is stopped or impeded partial or direct contact emerges causing intensive wear of rotors. Oil supply disturbances result in different wear caused damages not only of rotors but also other components [16]. Screw type compressor failures caused as a result of wear can be divided into restorable – the technological repair solution is economically remunerative, and unrestorable –restoration is not rentable.

2.1. Restorable failures

This sub-chapter analyses reasons of damage caused restorable failures –abrasive substances, lubrication, unsuited working environment conditions – and their consequences. Mechanical damages that are most often encountered are being analysed more in details. Analytical calculations as well as actual measurements prove that these damages affect compressor operation efficiency. Graphical depiction of profilogram allows to compare a new rotor with a worn one, shown on Fig. 2.1..



a)



b)

Fig. 2.1. Rotor surface profilograms

a) new rotor, b) used rotor

Theoretical mathematical coherence (2.1.) and graphical curve of changes of theoretical productivity Q_T (Fig. 2.2.) proves the influence of mechanical failure on compressor operation efficiency [32].

$$Q_T = \frac{\pi}{4} n_1 l (\Omega_1 d_1^2 + i_{21} \Omega_2 d_2^2) \tag{2.1.}$$

where: n_1 – rotation speed of driving rotor (rotations/minute);

l – rotor length, (m);

Ω_1 and Ω_2 – rotor cross-section useful area coefficient;

d_1 and d_2 – outer diameters of driving and driven rotors, (m);

i_{21} – rotor gear ratio.

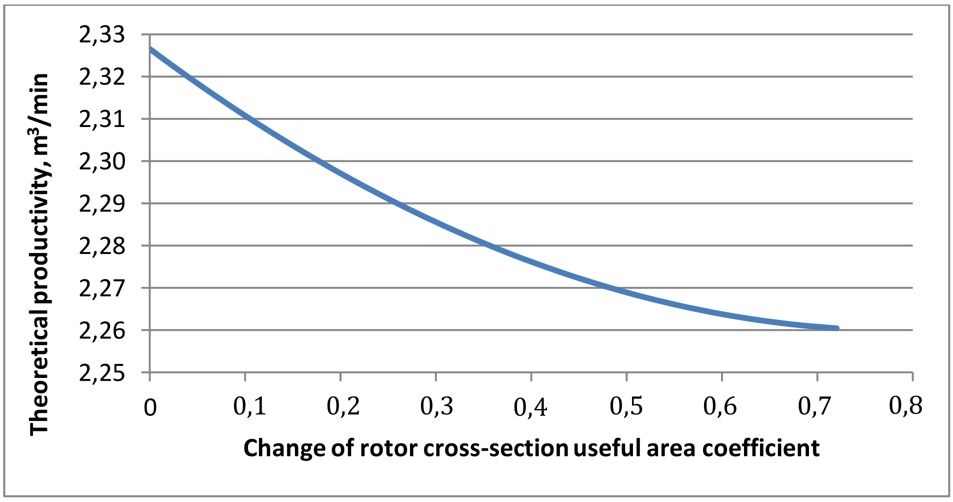


Fig. 2.2. Influence of theoretical compressor productivity depending on rotor wear size
(Informative)

2.2. Unrestorable failures

Reasons of most characteristic damage caused unrestorable failures are being analysed and encountered rotor damages shown. One of the most pressing unrepearable screw type rotor damages is ingress of large size foreign bodies between rotors, which can cause serious damages – creating cracks in rotor material (rotor consist with several parts) deforming their contact surfaces or even breaking them.

2.3. Conclusions

It was concluded in the Chapter that most characteristic failures of oil flooded screw type compressors are connected with inadequate working conditions, irregular servicing and failure of lubrication systems. This leads to considerable mechanical damages. Such damages lowers compressor capacity reducing the amount of flowing air – productivity and operation efficiency. To increase and restore compressor operation efficiency the reasons of mechanical failures or the caused consequences should be eliminated or minimised. Several solutions have been put forth for the prevention of work surface failures, for instance, to restore the initial rotor profile form, to make rotor from other material having better mechanical properties or to improve the existing rotor material.

Chapter 3. ANALYSES OF SCREW TYPE COMPRESSOR CE55RW ROTOR MATERIAL

3.1. Chemical analyses of rotor material

Since the manufacturer because of confidentiality reasons does not provide information on material used for rotor production and technological processes of obtaining semi-finished manufacture material, in order to choose the best solution for the restoration of compressor productivity or preservation and increase of operation efficiency one must carry out more detailed analyses of compressor rotor material. In cooperation with the Material Checking Laboratory of the Railway Transport Institute the chemical analyses of rotor material is being carried out (spectrometer *WAS PMI-MASTER PRO 13L0114*). The analyses results show that steel composition includes alloying elements. The amount of alloying elements is insufficient to ensure efficient compressor operation under changing operation conditions. According to the data of chemical analyses of material the materials of these rotors are made of quality carbon steel C35 EN 10025:02004. The carbon content is within the range of 0,35…0,36%.

3.2. Analyses of mechanical properties of rotor materials

To characterise and determine the correspondence of material of driven and driving rotor the characteristics of their main mechanical properties were determined. The ultimate tensile strenght and microhardness are main characterising values by the help of which the material correspondence, character and their shortcomings can be evaluated. The material ultimate tensile strenght at some rotor cross-section points for driving rotor Rm 412 N/mm^2, driven rotor Rm 417 N/mm^2 (*EQUOTIP dynamic portable meter),* microhardness for driving rotor HV 51 kg/mm^2 (measurements were placed on helical lobes cross-section area from rotor contact surface towards core), for driven rotor HV 60 kg/mm^2 (measurements were placed on helical grooves cross-section area from rotor contact surface towards core) (ПМТ-3 microhardness measuring device). The rotor material hardness like ultimate tensile strength is not unifrom at different cross-section points.

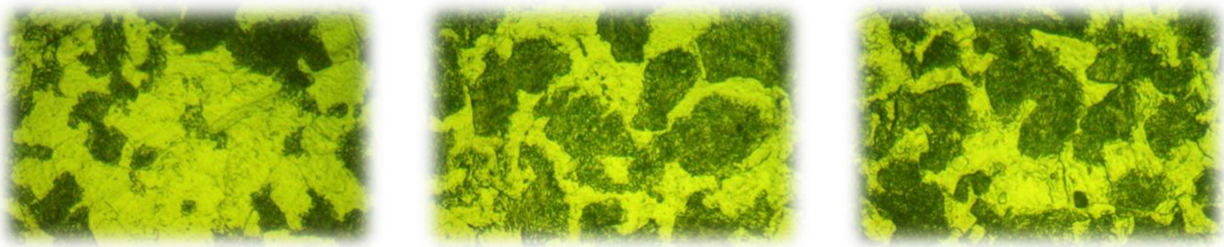
3.3. Analyses of rotor material macro and micro structure

The blank production method is being analysed by the help of macro-structure analyses. The rotor material cross-section surface is treated with Heine reagent. The material production method and following processing affects critically showings of mechanical characteristics of material. The macro samples of screw type compressor rotor material treated with Heine reagent are shown on Fig. 3.1..

Fig. 3.1. Rotor macro samples treated with Heines reagent

Macro samples treated with Heine reagent showed that screw type compressor rotor blanks are produced by casting, because on macro samples there was discovered macro structure of cast material which is characterised by three solidification zones shown on Fig. 3.1..

To be able to evaluate CE55RW rotor material and find causes of material non-uniformity the analyses of micro-structure of rotor material by metallurgical microscope IM 7000 at different cross-section points is being carried out within the framework of material analyses. The results are given on Fig. 3.2..



a) b) c)

Fig. 3.2. Rotor material micro-structure with IM 7000 100x/0,9 magnification

a) core part, b) towards upper layer, c) upper layer

By the help of this analysis one can assess micro-structure of the material, its flaws, structural imperfections and changes. Micro structure of the material is one of the main factors characterising the material affecting mechanical properties of the material.

3.4. Conclusions

As a result of analyses of screw type compressor CE55RW rotor material the following conclusions were drawn:

1) Chemical analyses showed that rotors are made of quality carbon steel C35 with small carbon content within the range from 0,35…0,36%;

2) Comparing to brand catalogue [34] mechanical properties of material are lower than were presented;

3) Non-uniformity of rotor material structure is related to cast material crystallization because the results of macro-structure analyses makes to conclude that rotor blanks were made by casting technology. Similarly the results of micro-structure analyses showed non-uniformity of micro-structure, proving that material structure at different cross-section points has been formed at different speed, thus changing the structure and mechanical properties of material.

The screw type rotor material analyses make to conclude that the existing mechanical properties of steel do not satisfy the prescribed operation specifications, thus the rotor contact surface wears out in a short time, reducing compressor operation efficiency. The rotor service life reduction reasons are mainly connected with low physical technical properties of material and non-uniformity of its structure. As a result materials with higher physical mechanical properties should be chosen for the production of these rotors, or existing material should be improved to ensure efficient compressor operation.

Chapter 4. ANALYSES OF COMPRESSOR ROTOR PRODUCTION TECHNOLOGIES AND RESERCH ON INCREASING SERVICE LIFE

4.1. Analyses of rotor production practice

Since one solution for reducing rotor failures (Fig. 4.1.) is to produce a new rotor from other material having better physical mechanical properties, in this Chapter having analysed the known curved surface production technologies a new production technology is being developed, including a process of material improvement treatment, envisaging improvement of rotor contact surface with wear-resistant coating to lessen the effect of abrasive substances.

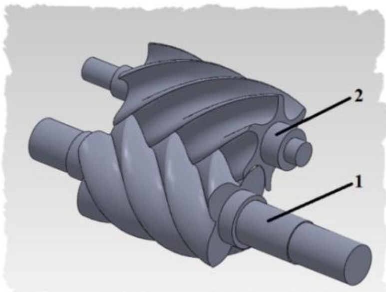


Fig. 4.1. Screw type compressor rotors

The analysis is being carried out based on the developed rotor production technology algorithm (Fig. 4.2.), starting from rotor designing until finished rotor.

When producing rotors the required predetermined rotor technical specifications must be ensured. To satisfy these requirements the rotor contact surfaces must be formed with high level precision and surface topography characterising parameters according to the predetermined requirements, for instance, roughness profile mean arithmetic deviation Ra 0,32…0,63μm.

Since the failure analyses showed that most often encountered failures are connected with mechanical damages of surface, attention is paid to the possibility to increase the contact surface's service life. Most well-known material strengthening methods are compared, for example strengthening with plastic deformation [1.30], thermal treatment [2], and chemical thermal treatment. Treating thermally oil flooded screw type compressor rotors the mechanical properties can be improved, not changing the chemical composition of the upper layer, and also wear resistance of rotor upper layer can be improved. Making thermal treatment the following shortcomings were stated:

1) Because of complex rotor profile its upper layer cannot be heated uniformly;

2) Rotors must be made of steel with carbon content not less than C>0,25%;

3) Proper cooling conditions cannot be ensured, as a result hardening defects - cracks, deformations arise;

4) Complicated form heating devices must be made.

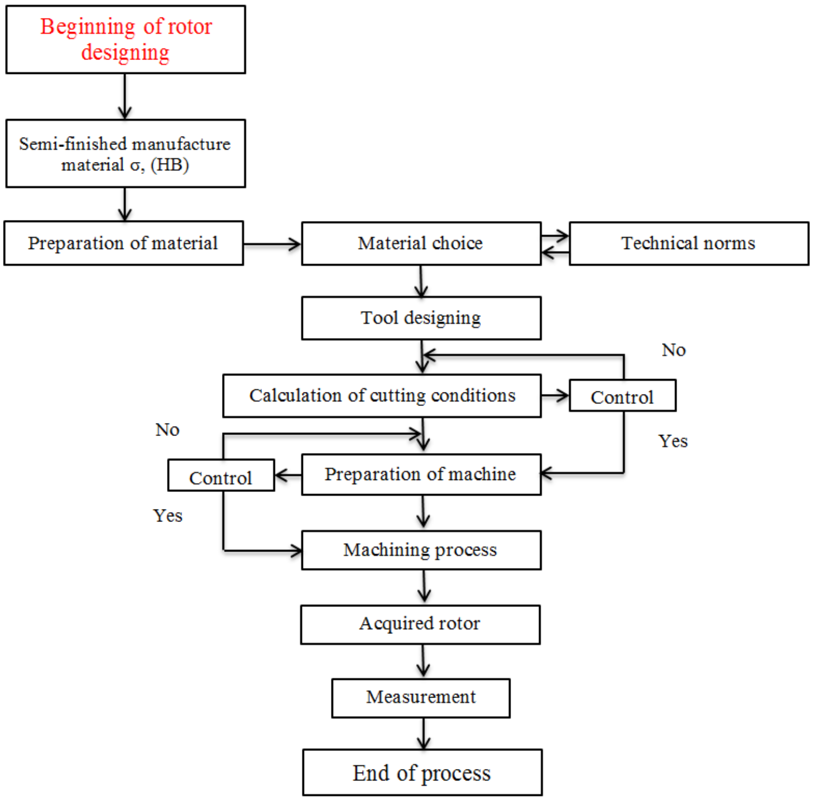


Fig. 4.2. Screw type compressor rotor production technology algorithm

The existing screw type compressor rotors are made of steel C35. The carbon amount it comprises is appropriate to expose material to thermal treatment for the improvement of mechanical properties. Without thermal treatment material hardness HV 123-167 kg/mm^2, ultimate tensile strength R_m 430 N/mm^2, yield strength R_e 215 N/mm^2 [34]. Treating screw type rotors thermally we get a material with improved mechanical properties shown in Table 4.1.

Table 4.1.

Mechanical properties of material after thermal treatment [34]

Material	C35	C55	30CrMoV
Quenching	850ºC	840ºC	880ºC
Cooling environment	Water	Water	Water
Abatement	500ºC	400ºC	500ºC
Cooling environment	Air	Air	Air
R_m	660	820	870
R_e	470	590	740
HRC	12	28	31
A	17	10	16

When materials are improved by thermal treatment a strong rotor core part is not preserved, and thus great attention is paid to advanced treatment technologies [2] for the strengthening of product's upper layer. Strengthening coatings are being applied. A material layer with much better mechanical properties than basic material is being deposited on the product's upper layer to increase hardness, wear-resistance and reduce friction resistance as well as to protect the product's contact surface from aggressive work environment. The screw type compressor rotor contact surface can be covered with, for example, TiN, Ti(CN), SiC, Mo_2N, TiAlN and other coatings. To increase the contact surface's service life the above upper layer improvement technological process should be included in the new rotor production process.

4.2. Analyses of material choice

This chapter deals with main provisions of material selection to choose rationally materials satisfying the prescribed rotor material requirements. When choosing material for rotor production one should choose material with higher hardness, higher ultimate tensile strength, that will reduce the surface wear intensity. As a result material for rotor production is offered. Since the choice of iron alloys is very wide their availability is unlimited and thus for the production of screw type compressor CE55RW it is recommended to choose a material from quality steel group – steel C55 or alloyed steel 30CrMoV.

4.3. Analyses of rotor nominal profile restoration possibilities

During operation the main operating parts of oil flooded screw type compressor rotors are exposed to high rotation speeds, varying and wide pressure ranges, varying cyclic stresses and different working environments. As a result of changing operation conditions rotor compatibility changes causing different irrevocable rotor operation failures. Rotor wear is being checked by measuring compressor productivity. When the compressor productivity has fallen by 15 % it is necessary to restore the rotor compatibility - rotor profile and pressure inter-space leak-proofness must be restored. This Chapter analyses several surface restoration solutions, starting from traditional ones till advanced restoration methods. The most rational restoration method is chosen according to several criteria [3]:

1) Wear size, type and character;
2) Economic considerations;
3) Chosen restoration technology;
4) Existence of repair base, raw materials and equipment, etc.

4.4. Development of mathematical expressions for modelling of rotor profile curve

When designing screw type compressor rotor profile there should be taken into consideration numerous compressor and its operation parameters connected with shaping of profile form, for example, theoretical productivity, gas to be pressed, operation temperature, air humidity, type of compressor drive and application field. Rotor profiles are shaped according to gearing theory. The screw type compressor rotor profile should be such that the screw's contact line, which is being formed when thread approaches groove, should be uninterrupted, starting from suction until outflow [32]. In the solutions of engineers' works one can find different rotor profile calculation methods. Using the analytical calculation method, by the help of different mathematical coherences one can describe precisely the rotor profile.

It follows from the gearing theory that one rotor profile peak can be chosen arbitrary, but the other rotor profile hollow must be found according to compatibility laws. When starting profiling the profile point coordinates in the transverse plane of one rotor, x_{01} and y_{01} and their first derivatives, either $\frac{\partial x_{01}}{\partial t}$ and $\frac{\partial y_{01}}{\partial t}$ or $\frac{\partial y_{01}}{\partial x_{01}}$ must be known. This profile may be specified on either the main or gate rotors or in sequence on both. If the primary rotor profile is being defined as a lobe shaft, turning angle between rotors Σ=0, envelope provisions for screw type rotors are determined according to coherence 4.1. [4].

$$\frac{dy_{01}}{dx_{01}}\left(ky_{01}-\frac{C}{i}sin\theta\right)+kx_{01}+\frac{C}{i}cos\theta=0 \quad (4.1.)$$

where: $k=1-\frac{1}{i}$ – coefficient;

C – distance of rotor interaxis, (mm);

$i=\frac{p_2}{p_1}$ – rotor gear ratio (p_1, p_2 – number of driving rotor lobes, driven rotor grooves);

θ – turning angle of driving rotor.

Where at rotor parallel axis the turning angle is $\tau=\frac{\theta}{i}$, the envelope profile coordinates for driving rotor in transverse plane are calculated according to coherence 4.2. [11].

$$\begin{aligned} x_{02}&=x_{01}cosk\theta-y_{01}sink\theta-Ccos\frac{\theta}{i}\\ y_{02}&=x_{01}sink\theta+y_{01}cosk\theta+Csin\frac{\theta}{i}\end{aligned} \quad (4.2.)$$

Further on we will study one of methods how to determine rotor profile coordinates and develop mathematical model for the description of the existing rotor surfaces. The method is based on graphical analytical method where by the help of toolmaker's microscope NMN-2 the coordinates of existing profile curve points are obtained. One peak axial profile of driving and driven rotor is being measured within one step. We equal the disposition of these points in space to the first approximation curves: linear, square a.o.. Using the least-squares method we approximate the adjustment coefficients to the used model, so that this model corresponds best to the rotor profile coordinate points gained in experimental measurements. Mathematical model development methods allow simple description of curve areas of any profile, which can be compared with theoretical profile curve, and simple designing of cutting surfaces of tools that will be used in rotor profile shaping in restoration technology. The functional coherence in mathematical form is put down as function according to coherence 4.3 [27].

$$y=f(x_1,x_2,...x_n) \quad (4.3.)$$

where: y – function;

x_1, x_2…x_n – arguments.

With the help of gained coordinate data the profile of driving rotor (Fig. 4.3.) is shown graphically in the two plane coordinate system together with theoretical curve.

After finding rotor profile curve coordinates mathematical systems are made, solving which we gain coefficients of chosen model curve area, which are used for making mathematical coherences, which in mathematical form are put down as a function according to coherence 4.3..

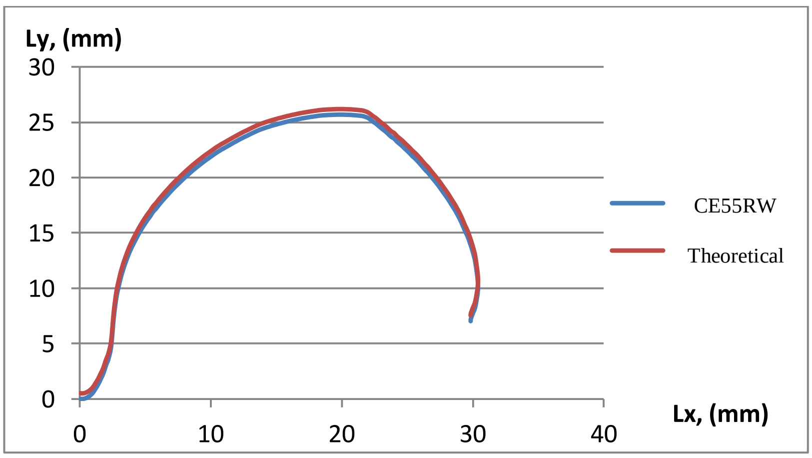


Fig. 4.3. Curve of driving rotor profile

Curves gained from coordinates are equalled to graphical coherences. The driving rotor profile was divided into four areas, where between the coordinate points x and y of this curve a square coherence 4.4. is being looked for, where a,b,c are constant coefficient – indecisiveness.

$$y = ax^2 + bx + c \tag{4.4.}$$

The curve points are situated on indeterminate parabola. Parameters of coherence 4.4 are chosen so that the sum of measurement error square is the smallest where provisions: $\frac{\partial u}{\partial a} = 0$; $\frac{\partial u}{\partial b} = 0$; $\frac{\partial u}{\partial c} = 0$ should be fulfilled. Gaining alterations to derivation functions y with variable coefficients a, b, c a mathematical system is established satisfying equation 4.5. system [29].

$$\begin{cases} a\sum_{i=1}^{n} x_i^4 + b\sum_{i=1}^{n} x_i^3 + c\sum_{i=1}^{n} x_i^2 = \sum_{i=1}^{n} y_i x_i^2 \\ a\sum_{i=1}^{n} x_i^3 + b\sum_{i=1}^{n} x_i^2 + c\sum_{i=1}^{n} x_i = \sum_{i=1}^{n} y_i x_i \\ a\sum_{i=1}^{n} x_i^2 + b\sum_{i=1}^{n} x_i^2 + nc = \sum_{i=1}^{n} y_i \end{cases} \tag{4.5.}$$

By solving equation system for each driving rotor profile area coefficients a, b, c of function 4.4. are found and the following mathematical coherences in a given interval are made.

Interval x (0,000-2,400)

$$y=1{,}018x^2-0{,}546x+0{,}075$$

Using the least-squares method the mathematical models of oil flooded screw type compressor rotor areas are made, which will help to design tool profiles for shaping driving and driven rotors when they are produced or during restoration process.

4.5. Tool designing methods

Development of mathematical coherences made in the previous chapter allows to produce a tool for rotor profile production. This Chapter analyses tool production methods. We will consider more in details a tool operating according to a envelope method which ensures rapid and precise treatment process.

For determination of profile of screw type compressor rotor manufacturing tool the following provisions should be satisfied:

1) To make an equation allowing to transform the prescribed coordinates of one mobile section into another system of mobile coordinates where profile of envelope tool is to be looked for;

2) To find a cluster of envelope curves.

The tool's initial coordinates can be described by coherences 4.6. [33].

$$\begin{aligned} x_0 &= r(\varphi - sin\varphi) \\ y_0 &= r(1 - cos\varphi) \end{aligned} \tag{4.6.}$$

where: r – initial circumference radius;

φ – rotor turn angle from initial position, which is equal to turn angle of mobile, immobile coordinate system axis.

For a simplified production of hob cutter tooth the complicated theoretical profile curve is substituted by circumference bow. The bow centre O_1 of circumference substituting the theoretical profile, coordinates x_0 and y_0 can be expressed by equation 4.7., using the analytical geometry coherences:

$$x_0 = \frac{(x_2^2 + y_2^2)y_1 - (x_1^2 + y_1^2)y_2}{2(x_2y_1 - x_1y_2)}$$
$$y_0 = \frac{(x_2^2 + y_2^2)x_1 - (x_1^2 + y_1^2)x_2}{2(x_2y_1 - x_1y_2)} \qquad (4.7.)$$

4.6. Conclusions

The analyses of the production of oil flooded screw type compressor rotor showed main aspects that should be considered in the production of their main components. One of the main aspects is to choose proper production technology and material. When choosing material envisaged for the production of compressed air up to 10 Bar high pressure it is advisable to select one from uniform steel rolled metal. Materials with much better mechanical properties that initial C35 steel were chosen and there were offered C55 quality carbon structure steel and 30CrMoV alloyed quality carbon structure steel with higher thermal stability that would serve rotors at increased temperatures.

Having assessed criteria determining suitability of restoration technology for elimination of high 100…2500 μm abrasive wear or damages, surface restoration is being determined by depositing coating by plasma or melting in electric slag.

Least-squares method allows approximation of adjustable coefficients to the used model so that this model would better correspond to the rotor profile coordinate points obtained in experimental measurements. In the chapter profile mathematical models were developed that would make tool designing easier. For more precise development of mathematical model profile curves were divided into several areas.

Having analysed the substantiation of the choice of tool, between instrument operation methods – envelope and copying – a tool was chosen operating according to envelope principle.

As a result of analyses of tool designing methods coherences were gained helping to describe the curve of tool cutting part. Since production of a complicated shape profile and cutting function provision is complicated the theoretical curve was substituted by a new circumference arc, as a result of which theoretical curve becomes simpler and tool production easier.

Chapter 5. PROVISION OF SPECIFIED PRODUCTIVITY OF SCREW TYPE COMPRESSOR BY VACUUM MADE COATINGS

5.1. Vacuum made coatings application technology

This section analyses advanced coating application technologies for elimination of small wears or strengthening of material upper layer:

1) Coatings are made by the help of chemical reaction (*Chemical Vapor Deposition* - CVD);

2) Coatings made by the help physical processes (*Physical Vapor Deposition* - PVD), during the process the evaporated material to be deposited settles on the basic material.

To test the coating's usefulness the samples are coated using the technology chosen as a result of analyses – cathode arc discharge deposition.

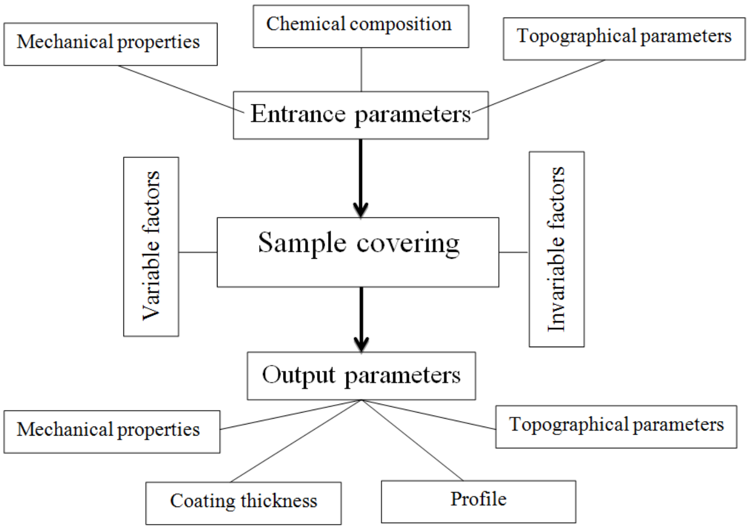


Fig. 5.1. Covering chart of screw type compressor contact surfaces

For experimental purposes surface of material under investigation is being improved by wear-resistant monolayer TiN coating, having better mechanical properties than basic material – higher hardness, wear-resistance, and smaller friction resistance. TiN has been chosen because it is being widely used as a protective coating in the manufacturing of different other products, to strengthen friction contact surfaces, as well as to extend their service life. The samples made according to the requirements to the new rotor contact surface production were covered in vacuum with the following set parameters (exciting current I, gas pressure P_N, voltage on the foundation U_{pam}, V_{ar}, deposition time T_{uzp}) shown in Table 5.1..

Table 5.1.

Main TiN coating application modes

Group	I_i, (A)	P_N, (Pa)	U_{pam}, (V)	V_{ar}, (Pa)	T_{uzp}, (min)
1. Group	80	$1 \cdot 10^{-3}$	140	$1 \cdot 10^{-3}$	20
2. Group	80	$4 \cdot 10^{-4}$	140	$4 \cdot 10^{-4}$	20
3. Group	80	$3 \cdot 10^{-3}$	140	$3 \cdot 10^{-3}$	20

5.2. Planning of experimental data processing

This chapter gives a short description of the experimental data processing, their meaning and methods. Within the experiment the prescribed sample data are measured with the precision for the equipment according to sample measurement procedure (Fig. 5.2.).

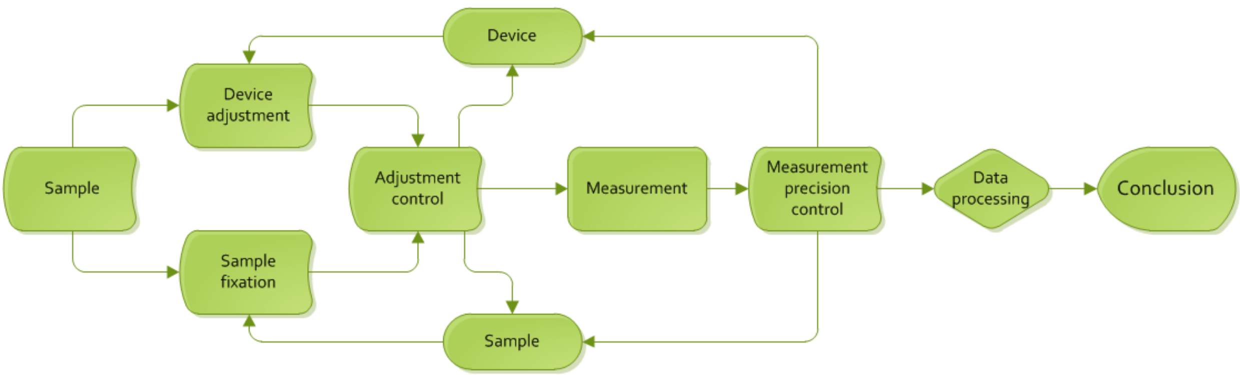


Fig. 5.2. Measurement procedure

The obtained measurement results were processed using mathematical statistics data processing methods.

5.3. Sample preparation procedure

For experimental purposes several samples were made being of equal worth to rotor material and having appropriate surface characterising parameters. In this chapter the sample production methods and meaning are being analysed. In view of the limited possibilities of measuring devices 12 samples made of C35 steel with definite chemical composition and mechanical properties (HV 123-167 kg/mm^2, R_m 430 N/mm^2, R_e 215 N/mm^2 were made for experiments [34]). Sample dimensions 30x30x5mm.

5.4. Analyses of changes of characterising parameters of screw type rotors improved with different coatings using vacuum technologies

5.4.1. Determination of thickness of made coating layer

Samples used in the experiment were covered with coatings based on TiN. The made sample groups differ in deposition procedures (Table 5.1.). When coating was deposited the characterising parameters of coating were determined – thickness of deposited layer. Measurements were made using optical microscope.

Fig. 5.3. Samples for coating layer thickness measurements

Table 5.2.

Coating thickness measurements and statistical processing of results

Samples groups	1. Group	2. Group	3. Group
Mathematical expectation value $\tilde{\mathbf{m}}$, µm	2,91	2,76	2,85
Dispersion $\tilde{\mathbf{D}}$	0,1121	0,1293	0,0783
Standard deviation $\boldsymbol{\sigma}_{\tilde{\mathbf{m}}}$	0,1059	0,1137	0,0885
Measurement relative error $\boldsymbol{\varepsilon}_{\boldsymbol{\beta}}$, %	5,98	6,78	5,10
Measurement credibility interval 1 Group	Iβ (2,804; 3,016)		
Measurement credibility interval 2 Group	Iβ (2,646; 2,874)		
Measurement credibility interval 3 Group	Iβ (2,761; 2,939)		

For visualisation of coating's layers optical microscopy was used – metallurgical microscope *IM 7000* from *Meiji Techno Inverted metallurgical microscope* series with 100x/0,9 lens and digital mirror camera Canon EOS 500D.

a) b) c)

Fig. 5.4. Digital pictures of coated samples in cross-section area
a) sample of group one, b) sample of group two c) sample of group three

According to the obtained measurement results of thickness of strengthening coating layer we can conclude that the thickest and most uniform coating reaching 2,91 µm, was observed in group one samples. Comparing (Fig. 5.4.) the cross-sections of coated samples among themselves we see that the cross-section of group three samples have marked unclear dark material areas, which might indicate a bad layer's ties with basic material. Such coating layer during operation as a result of small load will tend to separate from basic material.

5.4.2. Analyses of changes of coating's micro-hardness

For a more complete characterisation of coating's characterising properties and its effect on basic material the analyses of change of mechanical properties is made. The produced samples are analysed for changes of micro-hardness as compared with basic material and change of micro-hardness measuring from coating towards basic material [28, 30].

Fig. 5.5. General view on *ПМТ-3* measuring device

Several measurements were made for each sample at 0,5 mm interval and they were mutually compared within the group. Fig. 5.6. shows graphically the result measurements of group one samples.

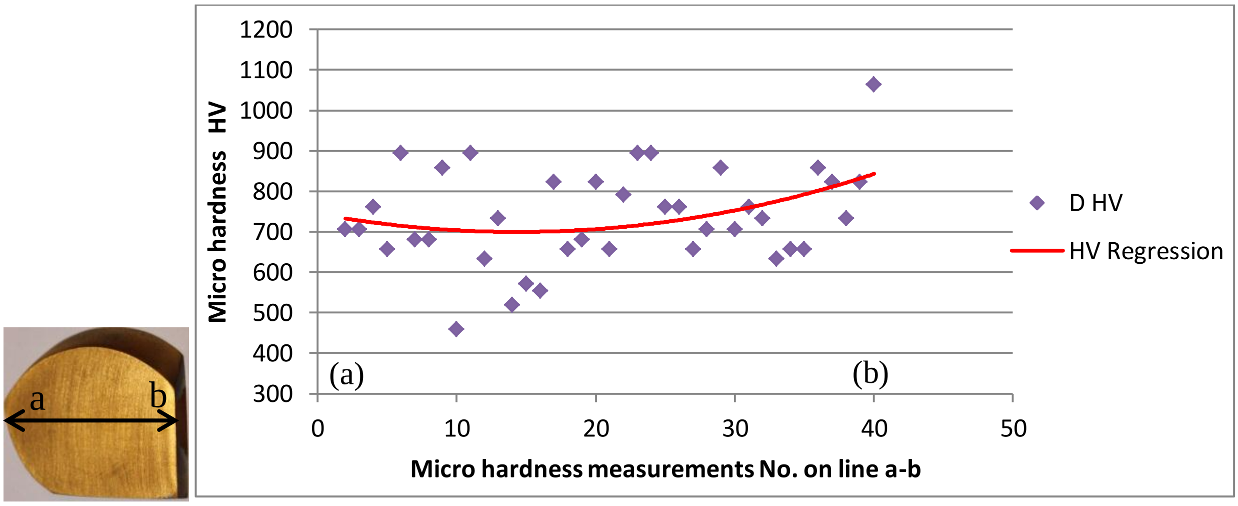


Fig. 5.6. Measurements of micro-hardness of group one surface strengthening coating

Micro-hardness of wear-resistant surface coating of group one varies within the ranges HV 456…1089 kg/mm^2 at an average value HV 695 kg/mm^2. Measurement error does not exceed 5% ε_β = 4,96 % and measurement credibility interval is I_β (660,414; 728,645).

The measurement result dispersion can be evaluated based on the micro-hardness random variable bar chart given on Fig. 5.7..

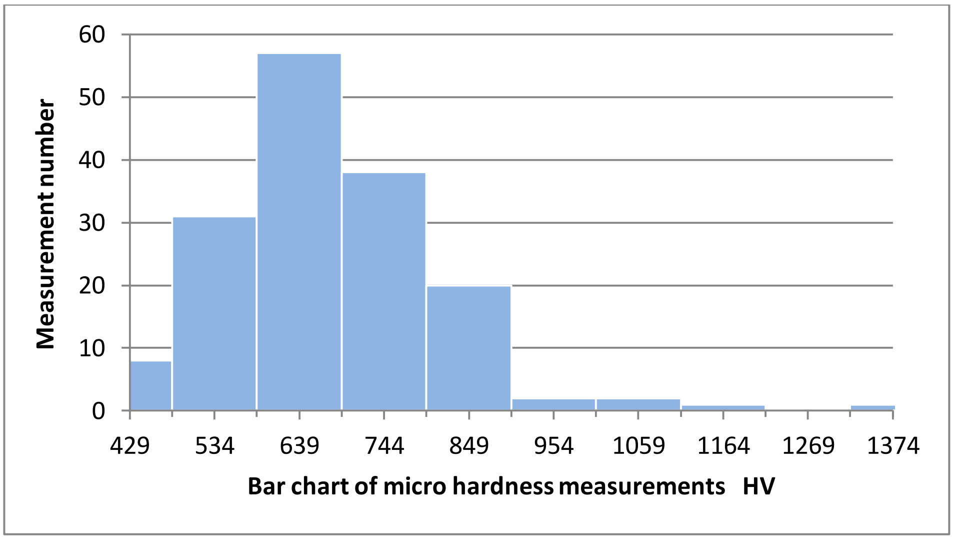


Fig. 5.7. Bar chart of surface strengthening coating's micro-hardness random variable measurements of group 1.

After statistical measurement result data processing the credibility intervals are calculated and graphically shown for all material groups (Fig. 5.8.).

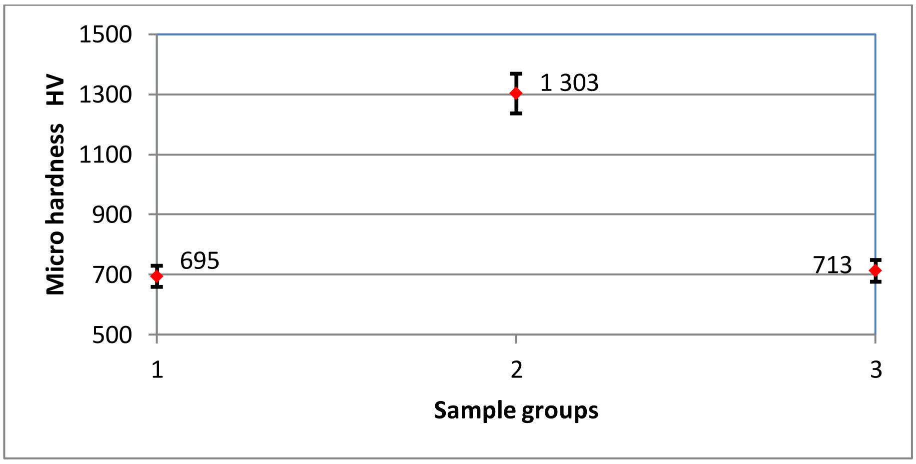


Fig. 5.8. Micro-hardness of surface strengthening coatings for all sample groups

Comparing mutually measurements of all groups, which are given on Fig. 5.8. together with credibility intervals one can conclude that the highest hardness of strengthened material can be observed in group two samples, yet the smallest credibility interval and smallest relative measurement error is characteristic of group one samples.

Table 5.3.

Changes of micro-hardness from basic material towards surface strengthening coating

Measurements	HV 1. Group	HV 2. Group	HV 3. Group
Nr.1	141	141	95
Nr.2	141	122	75
Nr.3	131	56	61
Nr.4	107	131	101
Nr.5	141	75	141
Nr.6	152	131	213
Nr.7	526	1030	526

To evaluate changes of mechanical properties of screw type rotor material, which were strengthened with TiN coatings, micro-hardness changes were evaluated in the direction from basic material towards surface strengthening coating. Thus it was found out whether the layer to be strengthened during covering has changed showings of basic material's mechanical parameters. The micro-hardness changes in all three groups are given in Table 5.3..

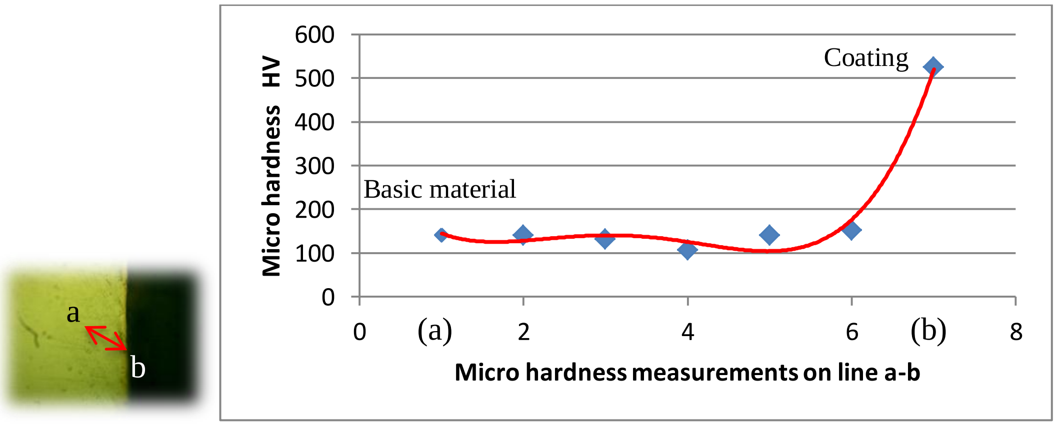
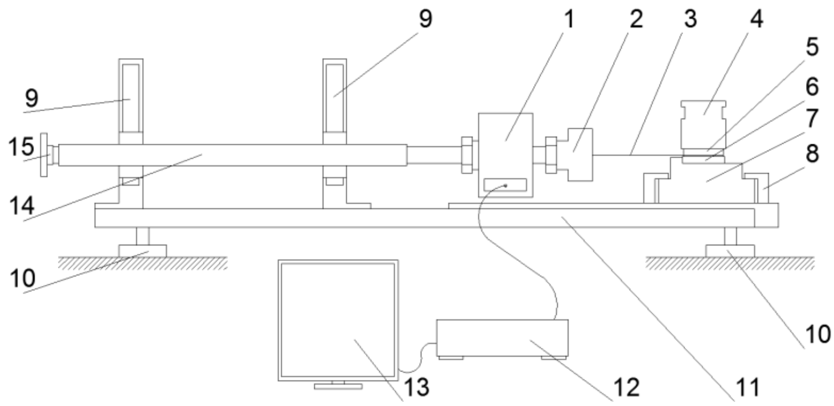


Fig. 5.9. Micro-hardness changes in the direction from basic material towards surface strengthening coating

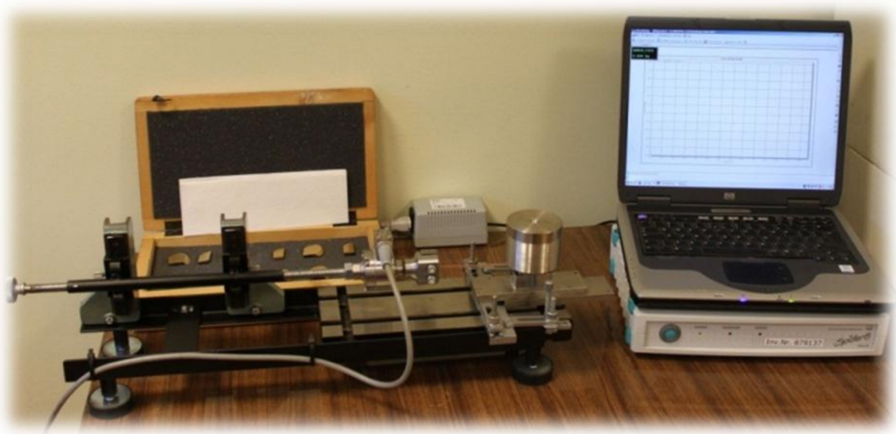
Analysing the obtained micro-hardness measurement results we can conclude that TiN coating does not change mechanical properties of the basic material.

5.4.3. Analyses of coating's friction coefficient changes

In each micro volume at friction cyclic stress changes take place, in the material border layers micro-damages are created based on the regularities of elastic plastic deformations. When making improvements of screw type compressor rotor contact surface it is important to obtain an upper layer with better mechanical properties, including with smaller friction coefficient that raises the compressor operation efficiency and increases the service life.



a)



b)

Fig. 5.10. Equipment for friction force determination

a) kenematic diagram 1) dynamometer, 2) gripper, 3) wire, 4) loading machine, 5) sample, 6) counter sample, 7) holder, 8) clamp, 9) regulated guides, 10) regulated foundation, 11) stand, 12) data reader, 13) data processor (PC), 14) traction mechanism guide, 15) traction mechanism, b) general view

Since in the screw type compressor there is a screw pair, both contact surfaces of which are covered with surface strengthening coatings, so both sample and counter sample have similar coatings and similar surface topography parameters. Measurements were taken both on samples and counter-samples without their wear-in. During the experiment friction force is being measured according to which both statistical coefficient in case of starting of rotor rotation and gliding friction coefficient during movement are calculated.

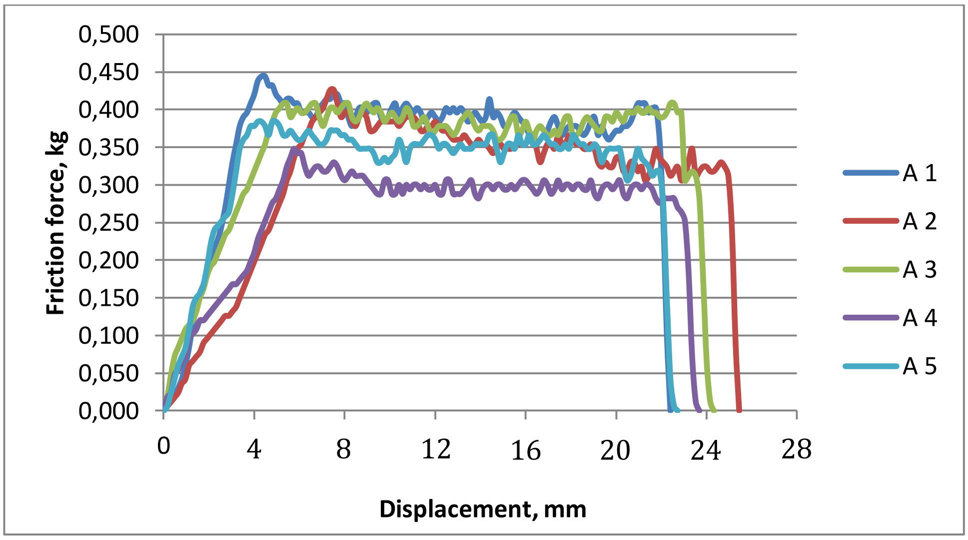


Fig. 5.11. Friction force measurements with TiN strengthened group 1 rotor material samples in case of dry contact

Table 5.4.

Group one sample measurements, calculation results

	Statistic friction	Gliding friction
Load m, (N)	14,2	14,2
Friction force max (N)	3,9	3,5
Friction coefficient μ_s, μ_{sl}	0,28	0,25

After the measurements of group one gliding friction forces (Fig. 5.11. and Table 5.4.) one can observe that friction force varies within the range F_b 0,32…0,39 kg with the average value F_{bvid} 0,36 kg. The measurement error does not exceed 1% $\varepsilon_\beta = 0{,}72$ % and measurement credibility interval is I_β (0,354; 0,359). Mutual comparison of friction forces of all three group samples is given on Figure 5.12..

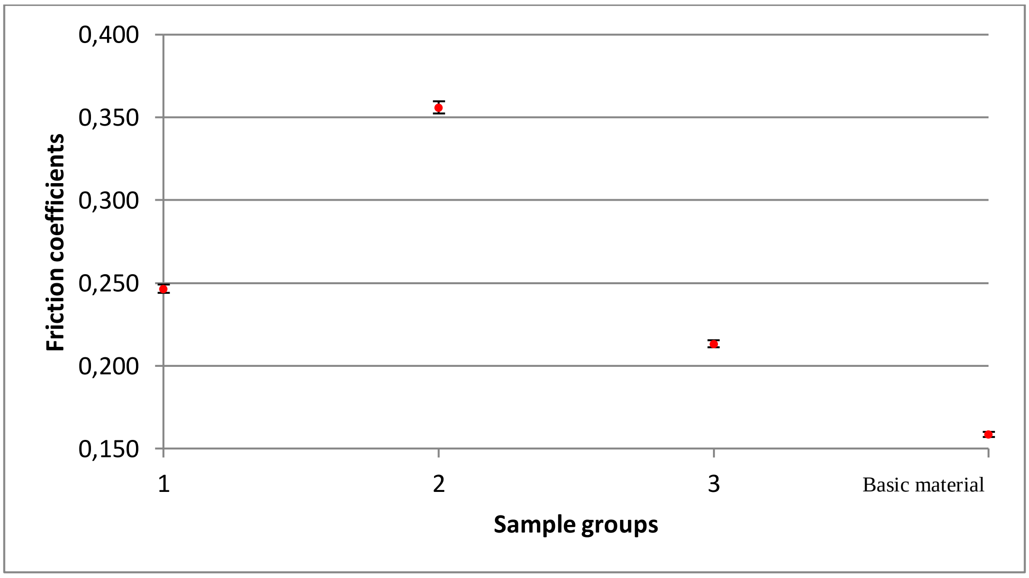


Fig. 5.12. Mutual comparison of gliding friction coefficients

Yet when making contact surface wear-in experiments it has been stated that after covering of contact surface with strengthening coatings and making its wear-in or final treatment which results in the reduction of large surface defects, friction coefficient is reduced by 8… 12%.

5.4.4. Assessment of coating surface's quality by a contact type roughness indicator

To be able to judge about the surface topography parameters, also about its quality and defects on it, which was shown by researches carried out in the previous chapter, after covering with TiN coating the contact surfaces were exposed to surface topography analyses by contact type meter 3D. 3D analyses most completely characterise micro level of sample's contact surfaces, providing information not only about main surface characterising parameters, but also characterises it with parameters of surface and volume parameter composition, spatial, functional and hybrid parameters. 3D analyses allow also to assess surface visually, giving a view on surface micro-roughnesses in general and its character in definite areas.

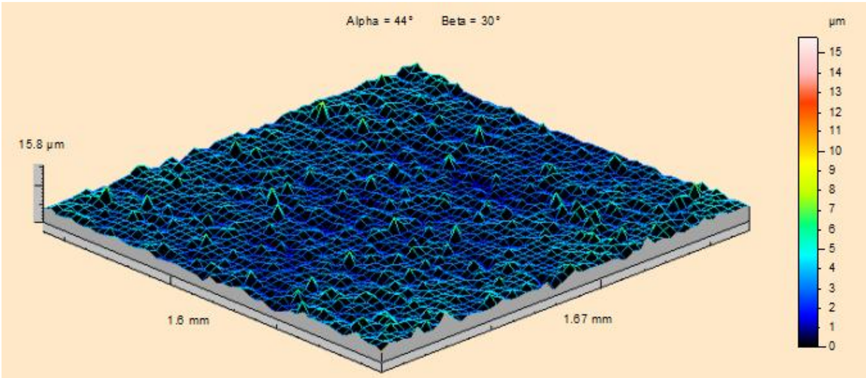


Fig. 5.13. Levelled 3D surface of covered group 1 sample (1,6x1,6 mm)

After covering samples with TiN material layer the data of analyses of 3D topography of main surface characterising parameters of group 1 samples and surface after levelling are shown on Figure 5.13. and in Table 5.5..

Table 5.5.

Data of group 1 covered sample topography analyses without wear-in

1. Group	**S_a, (µm)**	**S_z, (µm)**	**S_p, (µm)**	**S_v, (µm)**	**R_{a1}, (µm)**	**R_{a2}, (µm)**	**RS_{m1}, (mm)**	**RS_{m2}, (mm)**
Sample a	0,439	6,040	4,150	2,750	0,314	0,258	0,0580	0,0708
Sample b	0,528	7,560	5,950	3,120	0,521	0,294	0,0340	0,0356
Sample c	0,395	5,590	3,900	2,270	0,341	0,260	0,0434	0,0899
Sample d	0,392	4,300	1,310	4,260	0,359	0,285	0,0331	0,0594
Average	0,439	5,873	3,828	3,100	0,384	0,274	0,042	0,064

Comparing all surface topographies one can observe peculiar formations within the range 1,3…6,5 µm (peaks) situated chaotically on the surface. Irregular form roughnesses, as we see in the discussed topography measurements, change parameters characterising the rotor contact surfaces, for example, standard deviation from midplane has increased from 0,413 to 0,539 µm. In its turn when carrying out contact surfaces fastening experiments it was tested that after contact surface fastening that diminishes large surface defects, changes in the surface characterising parameters can be observed, for example Ra has diminished by 10-15%.

5.4.5. Assessment of covering surface quality by AFM

When studying the covered samples of screw type compressor rotor contact surfaces of all three groups one can observe spatial formations on the surface, different size and layout density surface lugs and hollows. To judge about the character and form of peaks the screw type compressor contact surface is subjected to surface quality analyses on nano scale, which is being carried out using atomic force microscope (AFM).

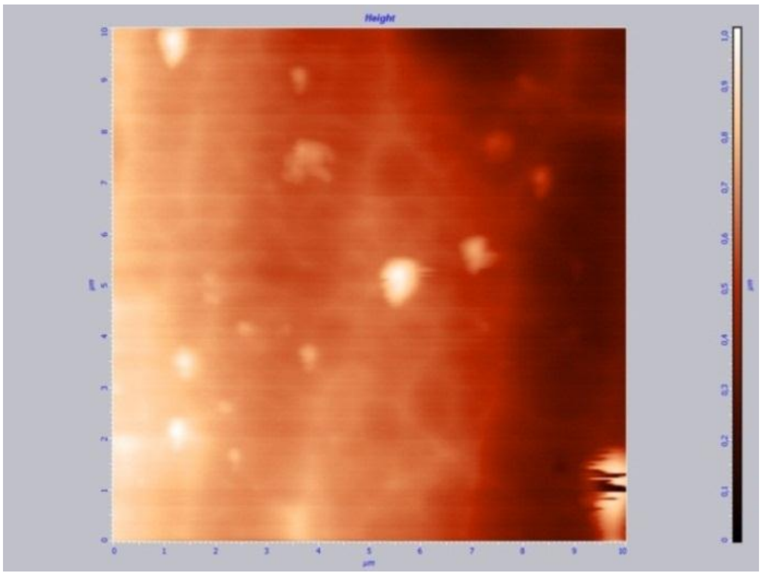


Fig. 5.14. Nano relief of AFM scanned surface of group 1 sample, relief representation (10x10 μm)

Analysing the defects encountered on the surface they can be divided into two groups:

1) Regular form defects – rhombic, circular. The sizes of nano relief defects of this strengthening coating vary within the range from 140…330 nm;

2) Irregular form defects –drops.

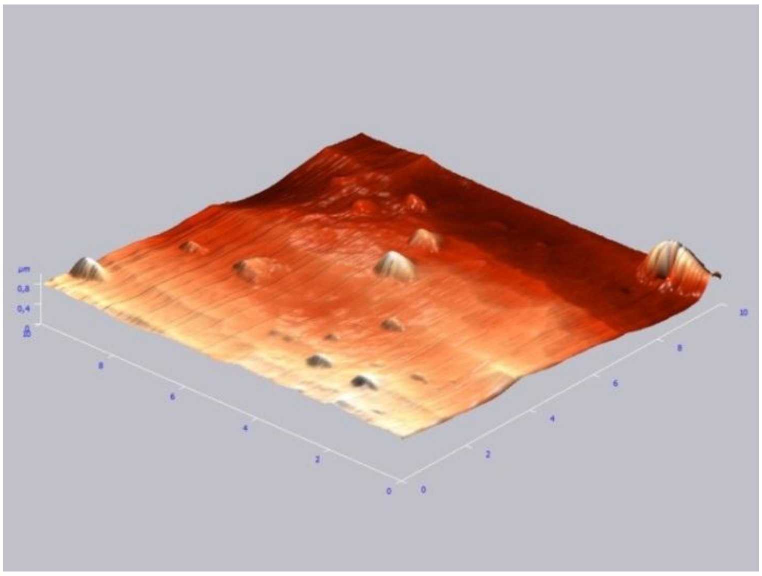


Fig. 5.15. AFM nano relief of group 1 sample, 3D representation

Table 5.6.

Characteristic quantities of nano relief of group 1 sample strengthening coating surface

Ra, (nm)	Rz, (nm)	Rq, (nm)	Ry, (nm)
147,876	522,168	177,797	1012,48

Examining the graphical representation of surface characterising parameters (Fig. 5.16.) one can evaluate surface uniformity and judge about its quality. The profilogram parameters shown on the above figure have been obtained analysing each scanned rotor contact surface area at an interval of 0,5 μm. A diagram (Fig. 5.17.) has been drawn for the comparison of all fastened rotor contact surfaces, which is characterised by changes of Ra – profile mean arithmetic deviation from midplane. We can conclude that the most stable Ra can be observed in group 1 samples and the lowest Ra value – in group 2 samples.

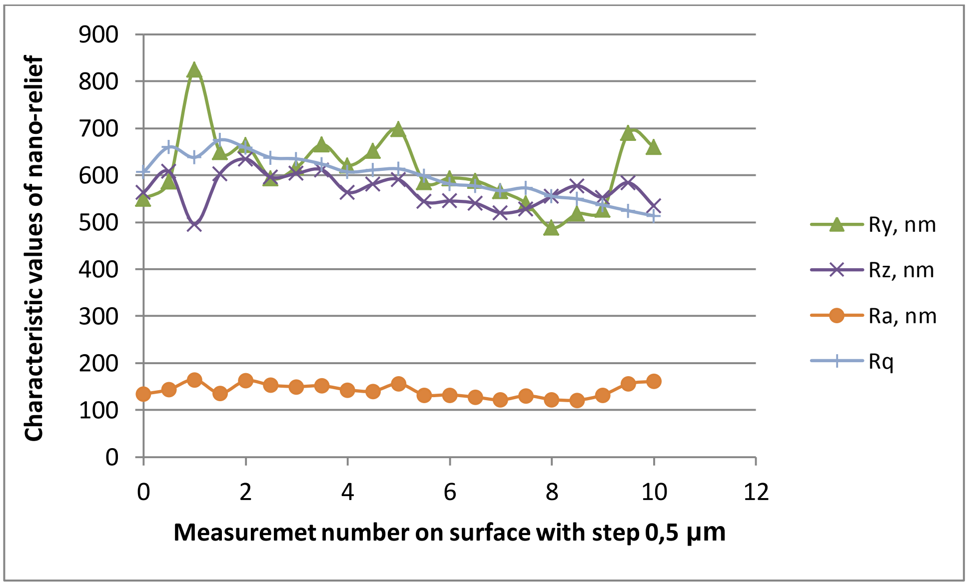


Fig. 5.16. Characteristic values of nano-relief of strengthening coating surface of group 1 samples

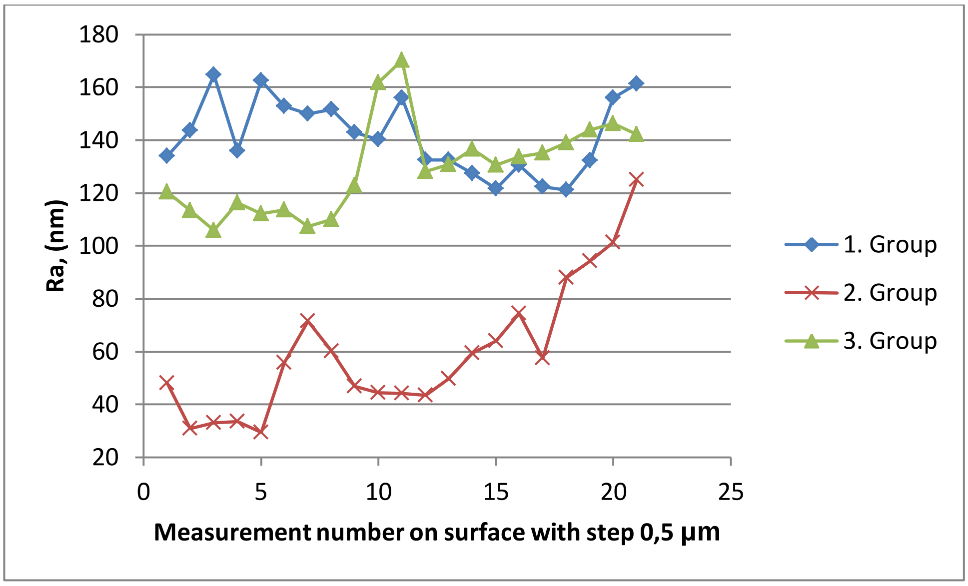


Fig. 5.17. Mutual comparison of Ra

Comparing mutually all three group coatings we can conclude that variable working pressure of coating process affects surface nano-relief very little. The covered material defects in the form of drops and hollows are observed on all contact surfaces. Making measurements repeatedly on the same samples after some time no surface relief changes were detected. Thus it can be concluded that coating and formed defects are stable in the sense of time.

5.5. Serviceability prediction methods of covered rotor contact surfaces

This chapter develops methods for the evaluation improvement efficiency of oil flooded screw type compressor rotor contact surfaces. It is needed to assess possibilities how to extend the rotor service life. The methods offer two criteria:

1) Criterion based on rotor surface's contact type – contact type coefficient k_T;

2) Criterion that takes into consideration the wear process course –wear effect coefficient k_d.

Contact type coefficient. Calculations analyse several surface parameter criteria, which influences essentially operation of contact surfaces. For this purpose contact criteria are stated for initial (uncovered) surfaces and resulting (after covering) surfaces. Since two surfaces are in constant contact, in the contact of component surfaces mutual impact of contact surfaces is characterised by contact criterion (KK). The contact criterion is determined according to coherency 5.1. [31].

$$KK = \frac{RS_{m1} H_{\mu}}{S_a E} \quad (5.1.)$$

where: RS_{m1} – mean roughness step in the cut perpendicular to friction pair movement direction, (mm);

H_{μ} – – micro-hardness, (kg/mm^2);

S_a – mean surface arithmetic deviation, (μm);

E – material elasticity module, (kg/mm^2).

Comparing the contact criterion initial values (KK) with obtained (resulting) contact criterion values, which are obtained after rotor contact surfaces have been covered with TiN, contact type coefficient k_T coherence is developed:

$$k_T = \frac{KK_R}{KK_S} = \frac{RS_{m1}^R}{RS_{m1}^S} \cdot \frac{S_a^S}{S_a^R} \cdot \frac{H_{\mu}^R}{H_{\mu}^S} \quad (5.2.)$$

where: indexes S, R characterise initial and resulting values.

The higher this KK value the component upper layer deformations become more elastic, thus the contact type coefficient must by larger that one ($k_T > 1$).

Table 5.7.

Values of contact type coefficient k_T

Covering group	Coefficient	Value
1. Group	k_{T1}	5,01
2. Group	k_{T2}	9,35
3. Group	k_{T3}	5,28

Analysing the calculation results (Table 5.7.) we see that application of coating, differing from each other by covering parameters, increases the values of contact criterion KK and increases essentially values of coefficient k_T. Hence it follows that coatings of compressor rotor contact surface under investigation raises the rotor wear-resistance.

Wear effect coefficient. To predict the product's service life changes we compared predicted values of wear. The wear value can be expressed by the following coherency 5.3. [26].

$$E\{U_n\} \approx k_m \cdot K_R \cdot K_{F-M} \cdot \frac{q}{E} \cdot S_a \cdot \frac{L_b}{S_{m2}^a} \quad (5.3.)$$

where: k_m – coefficient, which depends on fatigue curve parameters (N_o, m);

K_R – set of surface roughness parameters (R_a; S_{m1});

K_{F-M} – set of physical mechanical parameters (E; σ);

q – relative pressure on contacting surfaces;

E – material elasticity module;

S_a – surface mean arithmetic deviation;

L_b – friction path;

S^a_{m2} – mean profile roughness step in slit in the direction of friction pair movement for active surface.

For mutual comparison of wear value a wear impact coefficient expression is developed (5.4.).

$$k_d = \frac{E\{U_n\}^S}{E\{U_n\}^R} = \frac{K_R^S}{K_R^R} \cdot \frac{S_a^S}{S_a^R} \qquad (5.4.)$$

where: $E\{U_n\}^s$ – wear level for contact surface without wear-resistant coating (initial);

$E\{U_n\}^R$ - wear level for contact surface with TiN coating (resulting);

Indexes S, R characterise initial and resulting values.

The smaller the value of material with wear-resistant coating $E\{U_n\}$ the smaller the component wear, thus the wear impact coefficient according to coherence 5.4. must by larger that one (k_d >1).

Table 5.8.

Values of wear impact coefficient k_d for surfaces with TiN coating

Coefficient	Value
k_{d1}	1,31
k_{d2}	1,12
k_{d3}	1,06

Analysing the contact surface improvement efficiency according to criteria offered by the developed methods we can conclude that values of coefficients k_T un kd for rotor contact surfaces with TiN coating are >1. All technological improvements for rotor contact surfaces with TiN coating make surface contact more elastic, reduces the level of wear. Hence it follows that product's service life will be extended.

5.6. Conclusions

When analysing the possibilities to ensure the oil flooded screw type compressor operation efficiency a possibility was analysed to cover rotor contact surfaces with wear resistant TiN material, having better mechanical properties than basic material. For testing the hypothesis advanced for experimental purposes (whether TiN coating improves physical mechanical properties of contact surface, increases wear-resistance and service life) samples were made and they were covered with strengthening coatings, using PVD method – cathodic arc deposition forming coating by the help of physical processes. Functional properties of coating's material are being formed on the level of separate atoms and molecules.

According to the preset coating parameters (Table 5.1.) the coating thickness was created within the ranges from 2,76 µm to 2,91 µm. Analysing the changes of mechanical properties it was concluded that these improvements of contact surfaces increase many times the rotor surface mechanical properties, micro-hardness grows from 127 to 1302 kg/mm^2, ultimate tensile strength – Rm changes from 415 to 540 MPa, and the deposited layer changes very minimally properties of the basic material, preserving the basic material plastic.

Within the analyses of covering material the friction coefficient for contact surface was determined. Its increase was observed (Fig. 5.12.). In its turn, when carrying out contact surface wear-in experiments it was tested that after covering contact surface with strengthening coatings and wear-in them or making final treatment the large surface defects are decreased, the friction coefficient falls by 8…12%.

Regarding irregular form roughnesses, shown by topographical measurements, one can observe changes of characterising parameters of rotor contact surfaces, for example, the mean arithmetic deviation from mid-plane has grown from 0,413…0,539 µm.

After covering rotor materials defects can be observed on the surface, causing coating's porosity. Researches of several authors [5; 9] have pointed out that these defects are formations of micro-drops emerging during the coating process, when applying cathodic arc deposition in vacuum, or because of insufficient substrate temperature, which has been insufficient for the covered material to melt. Comparing mutually all three group coatings it is concluded that varying operation pressure during covering process affects very little surface's nano-relief. Defects of covered material, both in the form of drops and hollows, are discovered on all contact surfaces. When measuring repeatedly the same samples after a four month interval no changes of surface relief were stated. Thus it is concluded that the coating and defects on it are durable in the sense of time.

To judge about the improvements of oil flooded screw type compressor rotor contact surfaces the methods were developed offering two criteria:

1) Criterion based on the contact type of rotor surface – contact type coefficient k_T (5.2.);

2) Criterion considering the wear process course – wear effect coefficient k_d (5.4.).

Assessing the efficiency of contact surfaces' improvements according to the criteria offered by the developed methods we can conclude that for rotor contact surfaces with TiN coatings values of coefficients k_T un kd are >1. Hence it follows that in this contact there is an elastic contact, as a result of which surface roughnesses are deformed elastically and separation takes place due to fatigue. With the decrease of wear level the product's service life will be prolonged. Thus these technological solutions should be regarded as good ones and should be introduced into practice. It should be marked that these developed assessment criteria of treatment technological processes can be used for the assessment of efficiency of not only coatings but also different other technological processes or other results, related to the study of wear process.

WORK CONCLUSIONS

Nowadays use of compressed air is becoming more and more important in different branches of industry. Consumers are willing to use equipment that can operate without failures in a longer period. With the change of working environment and working conditions the compressor work resources are increased or reduced significantly. In the researches of Doctorate's work much attention is paid to factors affecting compressor operation efficiency.

In the Doctorate paper "Research on the increase of wear resistance of contact surfaces of screw type compressor rotors" the following results were reached:

1. According to the analyses of screw type compressor design and rotor contact surfaces it is concluded that screw type rotors are main compressors' working parts affecting significantly the compressor operation efficiency.

2. As a result of rotor failure study we can conclude that most characteristic failures of oil flooded screw type compressors are connected with significant contact surface damages, which increase air leakage and thus reduce compressor's productivity and efficiency.

3. Within the mathematical modelling of geometrical forms of rotors and treatment tools there were established mathematical coherences of rotor profile curves, allowing perform modelling of cutting tool profile for profile making or shaping.

4. As a result of study of technological solutions for the increase of rotor contact surface wear resistance it was concluded that it is more rational to use the existing rotor surface improvement technology with wear-resistant monolayer TiN coating, which simultaneously at small wearings restores the initial profile form.

5. Methods developed for the assessment of efficiency of contact surface treatment technological processes propose to analyse the contact surface according to two criteria:

1) Criterion based on the contact type of rotor surface –k_T (5.2.);

2) Criterion considering the wear process course –k_d (5.4.).

According to the researches and experiments carried out within the Doctorate work one can conclude that the wear-resistant TiN coating improves the physical mechanical properties of contact surface, increases wear-resistance and service life of oil flooded screw type compressor contact surfaces. These technological solutions are recommended for introduction into production processes. Thus one can declare that the objective set forth in the Doctorate paper has been achieved.

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