Thin coatings for pumping station mechanical components

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Abstract. The pumping stations are key points of water treatment plants, their performance directly affecting the serviceability of the entire water treatment system. The excessive wear of mechanical components conducts to pumping station out of service state. The deposition of thin coatings on the elements subjected to wear can generally extend the operating time of the water treatment plants. The paper analyses the failure modes of the mechanical components of the pumping stations and the existing efficient solutions for thin coating deposition to protect them from excessive wear. Consequently, an effective coating is deposited on the raw metal by Atmospheric Plasma Spraying (APS) and tribological tests are developed for an initial assessment of the anti-wear properties of the coating. The worn contact surfaces are analysed by Scanning Electron Microscopy (SEM) and the chemical composition is established by Energy-dispersive X-ray spectroscopy (EDS). The tests are still in development, revealing that the main failure modes of the coating are abrasive wear and delamination. Future research will be conducted to identify the best combination of powders for a multiple layer deposited coating with high wear resistance.

1. Introduction

Water resource, wastewater treatment, and wastewater reuse are important aspects of modern life. The reliability of wastewater treatment plants is mainly affected by treatment effectiveness, probability of mechanical failures, and impact of mechanical failures upon the effluent quality. The evaluation of the mechanical reliability of a treatment system means the precise identification of the key pieces of equipment whose failures may affect the normal functioning of the plant according to design specifications [1]. The analysis consists in creating a list of such mechanical weaknesses of the plant. From mechanical viewpoint, the pumping stations are key points of water treatment plants, their performance directly affecting the serviceability of the entire water treatment system. The excessive wear of mechanical components conducts to pumping station out of service state. The main mechanical problems in pumps consist in complications related to seals, bearings, proper lubrication, shaft, and impeller. The first two mentioned setbacks depend on mechanical engineering abilities to choose the right solutions [2]. For example, in high speed pump applications the user can choose between various solutions for shaft support: antifriction ball/roller bearings vs. hydrodynamic/hydrostatic sleeves, or magnetic bearings. Other difficulties are connected to the corrosion of pipe sewage systems [3] and pumps [4]. The deposition of thin coatings on the elements subjected to wear can generally extend the operating time of the water treatment plants, especially in aforementioned
cases [2-4]. From mechanical viewpoint, it seems that the user can insure an extended reliability of the pipes and pumps equipment by proper design (suited materials and coatings).

In the first part of this paper some aspects regarding the main failure modes of the mechanical parts of sewerage pipes and pump components are presented. Consequent a case study on steel sample coated by aluminium oxide (Al₂O₃) deposited by Atmospheric Plasma Spray (APS) is presented, focusing on preliminary friction tests carried out on AMSLER tribometer. The wear trace was analysed by Scanning Electron Microscopy (SEM) and Energy-dispersive X-ray spectroscopy (EDS) methods.

2. Failure modes of sewage pipes and pump components
The main failures in sewage pipes and pumps of wastewater treatment plants which can be prevented by users by appropriate choice of materials, lubricants, and coatings are: corrosion, abrasion, adhesive wear, pitting, erosion, and cavitation.

2.1. Corrosion
The pipes [3, 5] and also many components of pumps [4] are subjected to corrosion damage. The endurance to corrosion of a nodular cast iron was investigated by Perju et al. [4] by polarisation resistance method. The corrosion rate of nodular cast iron in acid wastewater is 4.5 times higher than in neutral water [4]. A cost analysis of the corrosion in concrete pipes revealed that the suited choose of coating material is able to extend the service life [5]. Coatings as epoxy (Ep), polyurethane (PU), and combined epoxy - sodium silicate (Ep–SS) protect the pipes acting as barrier against aggressive environment, therefore reducing the corrosion rate. The corrosion rate was measured in accelerated tests by weight loss percentage (WL) technique [5]. The most resistant coatings in hydrochloric acid environments are those based on Cr-Ni, Ni-Cu and Ni-Mo, e.g., 20Cr 30Ni, 66Ni 32Cu, and 62Ni 28Mo. In mixed acid solutions the best corrosion resistance was obtained by 20Cr 30Ni coating [6].

2.2. Erosion
The slurry erosion is one of the main causes of deterioration of wastewater plants and sewerage pipes. The erosion of materials is produced by the impact action of solid particles (erodont) suspended in a fluid stream. The main factors affecting slurry erosion are: the velocities of the fluid and erodent particles, size, angle of impact, shape, hardness and number of erodents in the fluid stream, but especially the strength of a target material [7]. To increase the erosion resistance of AISI 316 stainless steel, cobalt-based and titanium-based alloys were deposited as a coating by shielded metal arc welding (SMAW) method. The titanium alloy coating proved better strength to erosion [8]. Ni-Al₂O₃ based coatings applied on a hydro-turbine steel (CA6NM) presented the highest erosion resistance for 40 % of Al₂O₃ in the Ni alloy [9].

2.3. Cavitation
The rapid change in pressure within a liquid conducts to the formation of small bubbles of vapour (small cavities) in places were the pressure is low. The bubbles implode when subjected to high pressure, generating an intense shock wave. If this is happening near a metallic surface, damages can occur. This phenomenon is called cavitation, and the resulting product is the cavitation wear. This kind of wear is commonplace in pump impellers, valves and inlet portions of casing, generally in places where a sudden change of liquid direction happens. The cavitation in pumps can be avoided by previewing suction pipes which can uniform the pressure of the liquid. Anyway, suction recirculation can happen when two identical pumps operates in parallel at a reduced flow rate, conducting to increased vibrations and/or cavity damage. The resistance to cavitation wear can be increased by deposition of hard ceramic coatings to impellers [11], or by using expensive stainless steel. References [10] and [11] recommend plasma sprays, thermal sprays (such as Stellite 6), reinforced epoxy coatings, unreinforced polyurethane coatings, and ceramic coatings. A good low cost coating is unreinforced polyurethane. When coatings are using it must be paid attention to the thickness of these
coatings, as a small interstitial space at the entrance of impeller can accentuate the cavitation phenomena. Coatings are recommended usually for the maintenance of larger centrifugal pumps; in this case the thickness of a coating cannot greatly affect their normal functioning [10, 11].

2.4. Abrasion
Abrasion wear is taking place whenever hard particles - generated by wear of improper lubricated contact surfaces, or coming from environment due to improper sealing - are trapped between two surfaces in relative motion. In pump applications, the abrasion wear can manifest on oil rings, bearings and impeller. Abrasion can also be found in some portions of casing, depending on the pump design. According to [10], at least 5% of the centrifugal pumps of petrochemical plants suffer from oil ring abrasive wear, diminishing bearing life from an estimation of achievable 6 years, to only 3 years. The materials of composing pump’s parts being in contact with the liquid must be carefully selected to obtain maximum resistance to corrosion and abrasion at functioning temperature. Abrasion wear affects especially the slurry pumps, the wear rate depending by nature (hardness), size and sharpness of slurry abrasive particles. If usually abrasion can be avoided by proper lubrication of contacting counterparts in relative movement, in pumps this is no more possible if the seals broke down, or in small irrigation pumps with the rotor supported by bearing sleeves lubricated by circulating agent (unfiltered water). The life of a pump handling abrasives can be doubled if its rotational speed is 20 decreased, being inversely proportional to the pump speed to the 2.5 power [10].

It is very clear that a good resistance of mating surfaces in relative movement to the action of hard abrasive particles can be obtained by hard coatings (alloys of Ti, W, Cr etc.). An extensive study on resistance of coatings to abrasion is presented by Wu et al. in [12].

3. A case study on wear modes of Al2O3 coated steel
A steel sample of P265GH (according SN10028: C: max 0.2; Si: max 0.4; Mn: 0.8-1.4; Ni: max 0.3; Cu: max 0.3 and S: max. 0.015) was coated with Al2O3 by Atmospheric Plasma Spray. Five repeated thin layers were deposited. The steel is characterized by good weld ability and a high resistance at high pressures tensile strength (MPa) 410–530 for 100mm nominal thickness. There is also renowned for the high standard behaviour at high temperatures and it is used in the gas and petroleum industry, as well as the chemical and petro-chemical industry.

Al2O3 is one of the cheapest coatings, as Aluminium is available in huge quantity in the Earth’s crust (about 8.23%). Aluminium has a low density and the ability to resist corrosion through the phenomenon of passivation. Its behaviour to dry and water lubrication friction remains an issue of interest for researchers. With this aim, tests were carried out on AMSLER tribometer.

3.1. Determination of friction coefficient on AMSLER machine
AMSLER machine is a very usual tribometer, employed to test to sliding and sliding /rolling friction different pairs of materials: disk on pad (sliding bearing setting), disk on disk (rolling bearing setting) etc. for dry and lubricated conditions, at various loads and speeds. A general view of testing machine is presented in figure 1. The P265GH steel coated by Al2O3 was tested against a disk made of AISI52100 bearing steel with a surface hardness 62 HRC in dry and water lubrication conditions (figure 2(a) and figure 2(b)). Different normal loads in the range of 10-70N were applied by dead weights method. The friction torque was monitored by a data acquisition system based on tensometric strain gauges system. The test rig and data acquisition system is presented on large in [13]. The radius of rotating tested disk on rolling direction and on axial direction is the same: R= 29.4mm. The pad of coated steel was maintained stationary during tests, the tests being of pure sliding.
3.2. Measurement of surface roughness on Taylor-Hobson profilometer
The roughness of the tested surfaces was measured using a 2D Taylor Hobson profilometer. The $R_a$ values of the coated sample on longitudinal and transversal directions were $R_a=5.5\mu m$ and $R_a=6.4\mu m$, respectively. The measured roughness of the rotating disk on radial and axial directions were $R_a=0.42\mu m$ and $R_a=0.48\mu m$, respectively.

3.3. Wear traces analysis
The wear trace of the tested coated sample was analyzed both by optical microscopy (Aigo GE5 microscope from x60, x180 and x540), and by Scanning Electron Microscopy (SEM) at different resolutions.

3.4. Chemical composition of the unworn coating and wear traces analysis
The chemical composition of the unworn coating and wear trace at different points was analyzed by Energy-dispersive X-ray spectroscopy (EDS). The results are indicated in the next section.
4. Results and discussions

4.1. Results on friction coefficient versus load

The normal load on stationary coated steel sample on rotating spherical steel disk were obtained for a load range of 10-70N and a speed of rotating disk of 100 up to 250rpm. The span of each test was exactly 5 minutes. Mean values of the friction coefficients were obtained by LabVIEW data processing, an image of the developed post-processing tool being represented in figure 3.

![Figure 3](image_url)

Figure 3. LabVIEW post-processing interface for mean friction coefficient computation.

For a constant disk speed of 100rpm, from figure 3 one can observe that the friction phenomena are dynamic, e.g., for a load of 6Kg (60N), the dry friction coefficient manifests between 0.225 and 0.33 (around a mean value of 0.276). The results of dry friction tests are summarized in figure 4, also for constant disk speed of 100rpm and dry conditions. For two sequential loading stages (from 10 to 70N - red bars, and a repeated tests for 10, 20 and 40N – blue bars), the overall coefficient of friction (COF) fluctuates around 0.275, indicating the dynamic friction phenomena of coating removal. It can be observed that after the first stage of tests (red bars), diminishing the load to just 10N conducted to an important increase of the COF. As the load increased from 10 to 70N, the coating removal was continuously, assuring solid film lubrication over the contact area, as proved by SEM and EDS analysis. Depending on the Al2O3 particles deposition on contact surfaces and the delamination process at increased load, COF had some variations. At 70N of load the wear scar attained a maximum value. When the test was repeated for 10N the COF value attained a maximum of 0.36. At such a small load the abrasive wear and delamination process of the coating ceased, as this process take place on the wear trace at the boundary between metal and coating, as seen from SEM and EDS results. In such conditions, the contact between the pad and the rotating disk took place mainly on metal to metal surfaces, its alimentation with aluminium oxide being stopped. Increasing the load again (blue bars), the abrasive wear of the coating and its delamination conducted to a decrease of the COF near to the
values of previous test series (red bars). This fact proves the ability of the Al₂O₃ coating to behave like a solid lubricant. Further test should establish the wear rate of the coating.

![Graph showing mean coefficient of friction (COF) vs. normal load.](image1)

**Figure 4.** Mean coefficient of friction (COF) vs. normal load.

The tests are still in development. After dry tests, the load was kept constant at 60N and the speed was increased at 200 and 250rpm, this time disk passing by tape water bath put in a little reservoir (figure 2(b)). The results are presented in figure 5. The COF values do not depend on speed, but when water was used as lubricant, the COF decreased at about one half of the dry friction value, the lubrication regime passing from dry to mixed, some of the applied load being supported by fluid water lubricating film. The deposited coating particles played also the role of solid lubricant, composing an water – Al₂O₃ lubricating mixture. This result proves the ability of Al₂O₃ coating to assure a satisfactory lubrication in water lubricated sleeves sustaining the rotor of the pumps. Future supplementary tests are planned in order to establish the wear rate of water lubricated Al₂O₃ coatings running against a bearing steel.

![Graph showing mean coefficient of friction (COF) vs. speed for dry and water lubrication.](image2)

**Figure 5.** Mean coefficient of friction (COF) vs. speed for dry and water lubrication.
4.2. Results of optical microscope and SEM analysis
The optical microscopy was used to capture overall images of the wear track (figure 6). SEM images of different magnifications are presented in figure 7.

![Figure 6. Optical microscopy of wear trace: abrasive wear (x 60 - left); abrasive wear and delamination (x180 right).](image)

![Figure 7. SEM images of wear trace: unworn coating – (a); boundary of worn and unworn wear trace with delamination (b), and worn surface with abrasion and delamination (c).](image)

In figure 6(a) one can observe the wear trace at x60 magnification, with abrasive wear thin ploughs and delamination of the coating at the wear spot limits. Figure 6(b) presents details of wear spot boundary, emphasizing the cracks of the coating. SEM analysis from figure 7 allowed the observation of the unworn coating with fine structure (figure 7(a)). From place to place there are some agglomerations of Al₂O₃. In figure 7(b), the boundary between worn and unworn coating is presented. Small cracks can be found, due to delamination process of the coating under the action of the contact pressure. An intimate structure of the worn surface shows the abrasion and delamination of the coating and oxide covered base material, with small cracks (figure 7(c)).

4.3. Results of EDS analysis on unworn coating
The results of EDS are presented in figures 8, 9 and 10. The EDS of the three zones of the wear trace, are proving that the oxide and aluminium on the wear traces diminished from unworn coating (figure 8) to the center of the wear spot (figure 10). In the unworn coating the content of oxides is 37.59%, and the content of aluminium is 53.32%. The iron is just 9.09%, this being detected in the substrate.
4.4. Results of EDS analysis on boundary of the wear trace (delamination zone)

Figure 9 highlighted that there are still oxides at the boundary delamination zone of coating, the percent being 25.66, but the aluminium was removed (5.66%), and the iron substrate (68.68%) came to light.

4.5. Results of EDS analysis on the worn surface

The content of oxides (about 10%) and aluminum (about 3%) decreased from the boundary of the contact to its center (figure 10), but they are still in a sufficient proportion to assure a solid lubrication regime at the center of the contact, even the main composition of worn surface was found to be iron (over 87%). The EDS prove the assumption that the coatings behaves like a solid lubricant reservoir, supplying in the contact zone Al₂O₃ particles from the boundary entrance of the contact to its center.
5. Conclusions
In the first part of the paper the main failure modes of mechanical components of wastewater treatment plants and especially of pumps are analysed. These are corrosion, erosion, cavitation, and abrasion.

In the second part of the article a case study is presented. A sample of P265GH steel was coated with Al₂O₃ by Atmospheric Plasma Spray (APS), about 5 consecutive layers being deposited. The resistance of the coating to wear was analysed by tests on AMSLER tribometer, running the coated sample against an AISI52100 rolling bearing disk at different loads and speeds, for dry and water lubricated conditions. The coefficient of friction (COF) was monitored, mean values being obtained by LabVIEW interface.

The wear trace on the coated sample was analysed by optical microscopy, SEM and EDS. It was found that the coating acts like a solid lubricant reservoir, supplying soft Al₂O₃ particles from the entrance of the contact, these particles being detached from surface by adhesion and delamination wear. The COF values for dry friction are relative high (0.275), but decreased to 0.15 when water was employed as lubricant.

SEM and EDS analysis revealed that there is always enough oxide and aluminium on the worn surface to ensure an acceptable coefficient of friction for water lubricated conditions, when the COF value considerably diminished, indicating a mixed lubrication regime.

Aluminium has a low density and the ability to resist corrosion through the phenomenon of passivation. Its behaviour to dry and water lubrication friction remains an issue of interest for researchers. The cheap Al₂O₃ coating could be a solution for the lubrication of hydrodynamic sleeves sustaining the rotor of water lubricated irrigation pumps.

Future test must focus on the wear rate of Al₂O₃ coating in long-lasting tests, both for dry and water lubrication.

6. References
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