Chapter 2

Effects of Applying WC/C Protective Coating on Structural Elements Working in Cavitation Environment

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Additional information is available at the end of the chapter

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Abstract

When designing the individual subassemblies of machines or entire devices one has to draw special attention to the resistance of the elements working there, to tribological damages (mechanical, fatigue, adhesion, abrasion, hydrogen and other damages) as well as to non-tribological damages (corrosion, diffusion, cavitation, erosion, ablation and others). The main purpose of this publication was to examine the influence of the applied WC/C protective coating deposited by PVD method on the cavitation wear processes of construction elements working in difficult cavitation environment. Two steels were selected for detailed examinations in the conditions of cavitation wear. The first one is P265GH steel commonly used for pressure devices working at elevated temperatures, with a ferritic-pearlitic structure, and the other derives from a group of stainless steels, i.e. chromium-nickel X2CrNi18-9 (304L) steel with an austenitic structure. The tests results obtained allow to conclude that the application of special low-friction protective coatings allows to reduce costs associated with selection of engineering materials for a substrate of constructional elements working in a cavitation wear environment. P265GH steel is 4 times cheaper than austenitic chromium-nickel X2CrNi18-9 steel, and if a WC/C coating is deposited in this case, this considerably extends the working time of such elements in a cavitation environment.

Keywords: cavitation, PVD, coating, WC/C, cavitation generator, computer simulations, physical simulations

1. Introduction

Since people have started to use engineering materials deliberately according to their possible applications, first problems were also identified at the same time, related to the strength of the elements made of such materials. Each modern engineer should be aware of this aspect in one's everyday work during which, when designing a specific constructional solution and selecting a material appropriate for it, one also has to foresee sometimes complex erosion mechanisms the element being constructed will be exposed to and prevent them effectively. For this reason, in parallel to the development of innovative solutions for fabrication and processing of engineering materials, knowledge has been developed in scope of their wear mechanisms, both, on the surface as well as in their core often representing a substrate. The character of the surface often has a direct effect on the product fabrication process, and its functional properties in many cases depend on the surface quality, including shape geometry, roughness, chemical composition, structure morphology or an external appearance. It is worth noting that requirements imposed on the product interior, representing a substrate or core, are usually different from those for the external surface of a given constructional element.

When designing the individual subassemblies of machines or entire devices one has to draw special attention to the resistance of the elements working there, to tribological damages (mechanical, fatigue, adhesion, abrasion, hydrogen and other damages) as well as to non-tribological damages (corrosion, diffusion, cavitation, erosion, ablation and others). Considering the above-mentioned mechanisms, cavitation erosion and wear are often overlooked in engineering design, the dual character of which has an effect on the economics and development of particular fields of economy in the negative and positive sense. Cavitation is generally described as a phenomenon consisting of implosion of gas bubbles in liquid, with such bubbles formed as a result of a rapidly falling pressure causing the creation of shock waves with the length of 0.1–0.2 mm and the speed of several hundred m/s, destroying local surfaces of elements and causing deep cavitation pits and craters. For example, the bodies of machines and devices and constructional elements working directly in a cavitation environment are exposed to long-term wear leading to damages and failures, which are disastrous in the economic sense, of complete assemblies, components or in exceptional cases single parts only. A negative impact of cavitation can also be diagnosed for water supply pumping stations used across the world. The cavitation wear resistance of a flow system of pumps and water supply systems depends on the type of the material applied and its surface treatment, including also its structure and properties. Cavitation pits forming in water supply system elements are typically found on the entire part surface, especially near scratches and surface defects created in a manufacturing process. Such scratches or material defects normally occur by accident in transport, maintenance or due to negligent operation. In processes related to transportation of medium, especially water, threats to a construction's reliability are often encountered due to cavitation wear processes of construction elements of the flow system in rotodynamic single- or multi-stage pumps working in water supply stations and systems, as well as parts of entire water turbine blades. The most effective way to mitigate the effect of cavitation in flow systems is to use materials resistant to cavitation wear for medium transportation constructions. Materials from the group of stainless and acid-resistant steels, i.e. bronze and brass, are thought to be the appropriate engineering materials which can be used in water supply systems and pumps [1–4].

The discussed issue of cavitation erosion does not apply to selected cases of water distribution or electricity generation only, i.e. to turbines operated in hydropower plants, but most of all to the whole water transportation infrastructure, to different types of power and heating assemblies and complexes working in plants producing electric energy and in combined heat and power plants producing electric and heat energy in cogeneration, in municipal heat distribution plants and in all types of systems distributing thermal energy in the form of steam or water. The power sector, heat distribution sector and heating sector are critical, essential and strategic branches of industry in any country, where potential failures very often materialise in high financial losses.

Additionally, apart from the negative consequences of material wear processes in a cavitation environment, technological solutions can be quantified employing cavitation processes in a positive context. The best example are materials treatment technologies, such as: cutting, drilling, water jet cleaning, emulsification technologies used in the chemical and petrochemical industry, techniques of ultrasound-induced joining or hydrodynamic cavitation applied for cleaning industrial water or effluent coming from municipal and domestic infrastructure. The techniques described, used in the materials industry, consist of, especially: technological flow of the water as a working medium where cavitation bubbles of a liquid containing water are flowing out of the device nozzle at a small rate (3 dm^3/min) to a given area with a very high pressure (350 MPa) [3–8]. On the other hand, high frequency 20–100 kHz ultrasound cavitation generators are employed for engineering materials surface cleaning techniques.

The heating and heat distribution sectors are also making efforts to use cavitation processes to heat up a heat carrier such as circulating heating water of a central heating system. The first example is a so-called cavitation pump, which is utilising mechanical energy, converting the energy into thermal energy through the centrifugal flow-based heating of water contained in a cavitation pump body. Such a solution is used as a house heating system especially in the United States or Australia. Another example is a patented method of heat production in buildings with the cavitation effect employing a phenomenon of whirling the flowing water ensuring the liquid cavitation effect. The technology of heat generation in a device involves the resonance amplification of sound and impact vibrations in the flowing liquid. In this process, mechanical energy is also converted into thermal energy through the flow pressing of water in a heating device [3–6, 10–24].

Undoubtedly, a cavitation effect as well as the inherent cavitation wear is an issue requiring further scientific and industrial research for describing and understanding fully and comprehensively the characteristics of the undesired issue such as cavitation wear and the accompanying phenomenon of degradation of the operated surfaces of engineering materials. For this reason, this chapter discusses the influence of an engineering material, representing a substrate for a cavitation generator, on the surface of which a coating was implemented, deposited by PVD, in order to substantially improve the wear resistance of a constructional element used in a cavitation environment. The dimensions and shape of the above-mentioned cavitation generators were also analysed using CFD simulation carried out with ANSYS FLUENT software in a custom-designed and fabricated stream and cavitation device with the flow character of work in a closed cycle [25, 26].

2. Computer simulation

Two steels were selected for detailed examinations in the conditions of cavitation wear. The first one is P265GH steel commonly used for pressure devices working at elevated temperatures, with a ferritic-pearlitic structure, and the other derives from a group of stainless steels, i.e. chromium-nickel X2CrNi18-9 (304L) steel with an austenitic structure. P265GH steel—due to its unlimited availability and attractive, low market prices—is used for constructing heat distribution devices and heating devices, and for less critical constructional parts. X2CrNi18-9 (304L) steel, which is five times more expensive than P265GH steel, is used for production of devices, apparatuses and fittings in the chemical, food, power and petrochemical industry and for constructional elements in the aviation and shipbuilding sector. A chemical composition of the structural steels tested in the conditions of cavitation wear is presented in **Table 1**.

Cavitation generators (**Figure 1**), with the shape and dimensions selected by analysing the results of numerical simulations in ANSYS FLUENT software, described in detail in the earlier publication, were prepared using the above-mentioned P265GH and X2CrNi18-9 (304L) steels [5]. The cavitation generators were tested in the conditions of cavitation wear continuously for 500 PMH (Productive Machine Hour) in a specially designed computer model (**Figure 2**), and then in a constructed author's stream and flow device (**Figure 2**) generating a cavitation environment. The detailed process parameters are presented and described in the publication [5].

It was found based on the computer simulations performed and the obtained numerical results of medium (water) flow at a temperature of around 40°C for the set boundary conditions that

Steel		Chemical composition										
		C [%]	Mn [%]	Si [%]	Al [%]	Cr [%]	Ni [%]	Cu [%]	Ti [%]	N [%]	S [%]	P [%]
P265GH	max	—	—	0.4	—	0.3	0.3	0.3	0.03	0.012	—	—
		0.16	0.99	0.23	0.047	0.027	0.013	0.026	0.001	0.003	0.008	0.019
X2CrNi18-9 (304L)	min.					17.50	8.00					
	max	<0.03	<2.0	<1.0	—	19.50	10.50	—	—	<0.11	<0.045	<0.015

Table 1. Chemical composition of the structural steels tested in the conditions of cavitation wear: P265GH by PN-EN 10028:2010; X2CrNi18-9 by PN-EN 10088 [mass fraction, %].

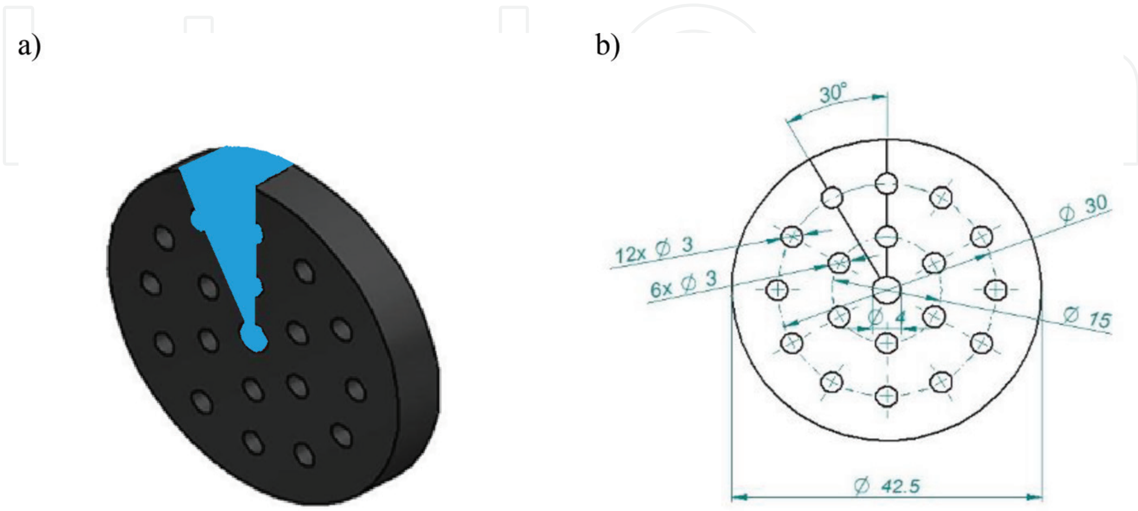

Figure 1. Cavitation generator model's dimensions and shape selected based on the analysis of results of numerical simulations in ANSYS FLUENT software; cavitation generator thickness of 5 mm, relative clearance of pp = 11.1 [%] [5].

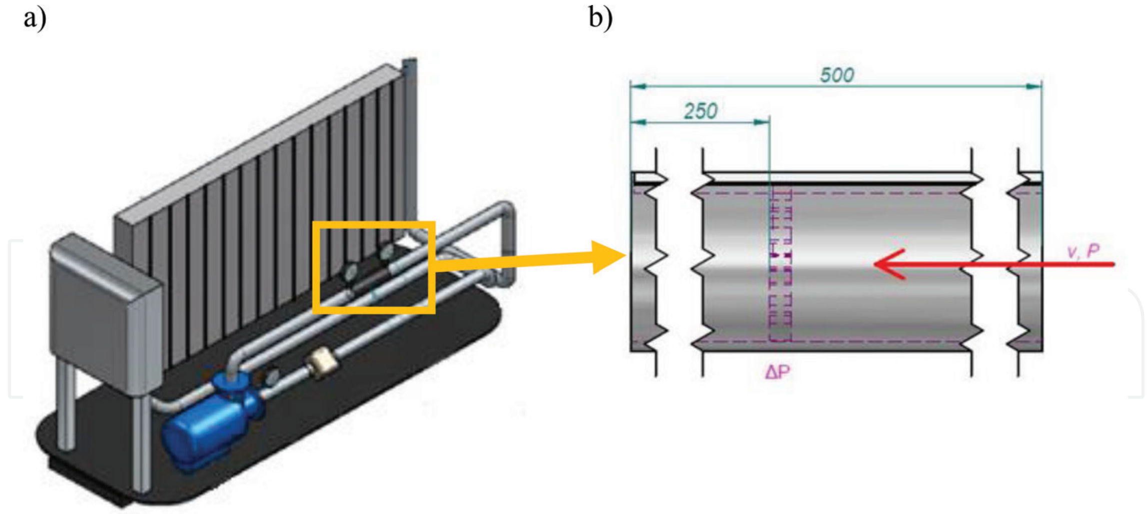

Figure 2. Model of a stream and flow device generating a cavitation environment; (a) isometric diagram of the device, testing and measuring system; (b) simplified computer model of the cavitation generator location with the medium (water) flow direction marked red arrow [6].

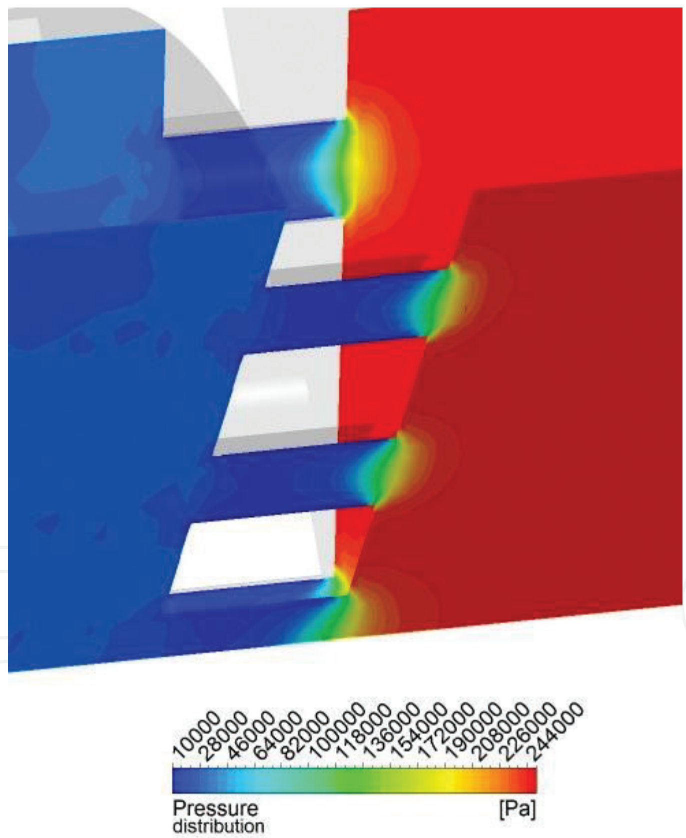

Figure 3. Pressure distribution of flowing medium (water) on the one-twelfth (30°) section of the field area of model of constructional element [5].

cavitation implosions (content of steam) simulating the wear are occurring to a high degree. Simulating the wear occurring mainly before a cavitation generator, and especially on the inlet edges and along straight-through openings of a constructional element. A cavitation generator

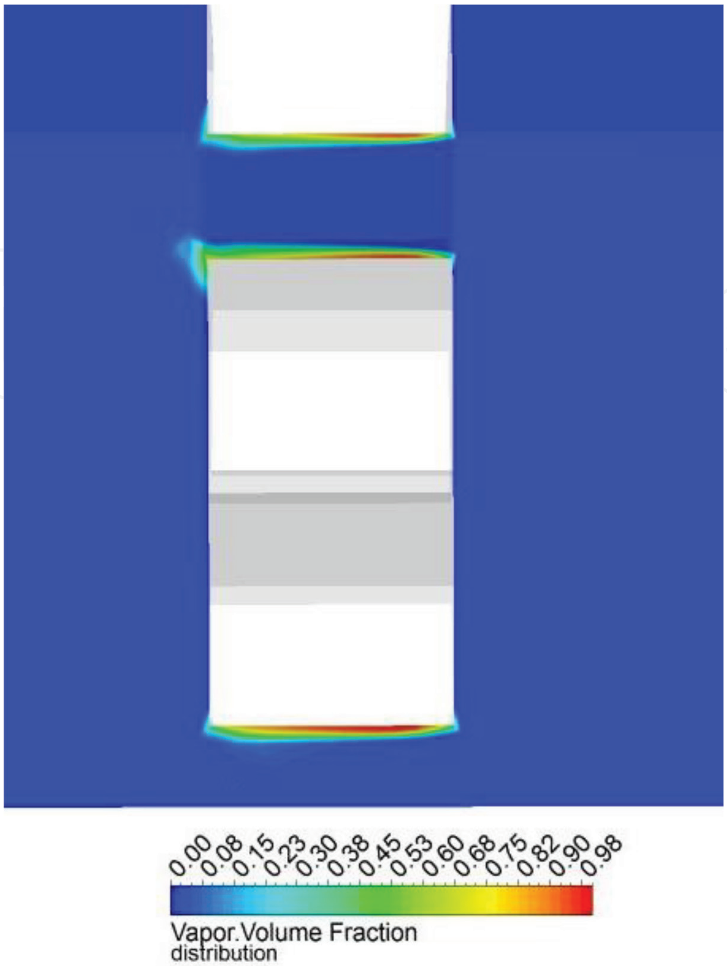

Figure 4. Implosion distribution in form of content of steam on the one-twelfth (30°) section of the field area of model of constructional element [5].

was selected characterised by a relative clearance Pp of 11.1 [%], which has reached an inlet pressure of the medium of 244,000 [Pa], for the number of cavitations (content of steam) of 0.98 [%], as shown in **Figures 3** and **4**. The areas most susceptible to cavitation wear were also defined by analysing numerical results, with such areas being most of all the areas of straight-through openings, and a central opening with the diameter of 4 mm was found to be most susceptible, in particular.

3. Results of physical simulations of cavitation generators without protective coating

Cavitation generators, made of two P265GH and X2CrNi18-9 (304L) steels selected for this aim, were then tested in the conditions of cavitation wear continuously for 500 PMHs, with a specially designed and constructed author's stream and flow device (**Figure 2a**) generating a cavitation environment. The impact of surface roughness was investigated before the operation of the generators in the conditions of cavitation wear on the roughness and a mass loss after the above experiment. For this reason, prior to installation of a cavitation generator in a stream and flow device generating a cavitation environment (**Figure 2**), as well as after

500 PMHs of continuous work in such device, the cavitation generator was cleaned in an ultrasonic cleaner, and then weighed on an analytical scale, AS/X by RADWAG. Surface roughness was determined with a Surtronic 25 contact profilometer by Taylor Hobson. At least 4 measurements, along the length of 16 mm in different areas of the constructional element, were performed to determine surface roughness of each generator. Detailed macroscopic examinations with a scanning electron microscope, SUPRA 35, at the accelerating voltage of 5–20 kV using secondary electrons (SE) detection, with the magnification of 100–2000×, were undertaken for preliminary identification of the cavitation wear results [6].

The results of mass loss and surface roughness measurement examinations before and after use are shown, respectively, in **Figures 5** and **6**.

The results of macroscopic examinations of the applied P265GH and X2CrNi18-9 (304L) steels in conditions of cavitation wear made with a SUPRA 35 electron scanning microscope using secondary electrons (SE) detection are shown in **Figures 7–10**.

A constructional element such as a cavitation generator made of ferritic-pearlitic steel, designated as 200-P265GH, wet sanded with sandpaper with the grain size of 200, weighed 57.6271 g before use and featured a surface roughness factor R_a of 0.627, thus falling to the 8th surface roughness class according to PN-EN ISO 1302:2004. A negligible mass loss of approx. 0.03 g was also found as a result of generator operation and a roughness factor R_a fell from 0.627 to 0.41, which is further classified as the 8th surface roughness class. A constructional element made of ferritic-pearlitic steel designated as 1000-P265GH, i.e. wet sanded with sandpaper with the grain size of 1000, had the weight of 57.1835 g and a surface roughness factor R_a of 0.15, thus falling to the 10th surface roughness. The highest mass loss, of as much as 0.1752 g in relation to all the operated generators, and the growth of the roughness factor R_a from 0.15 to about 0.5, was found after operating a generator marked as 1000-P265GH, which

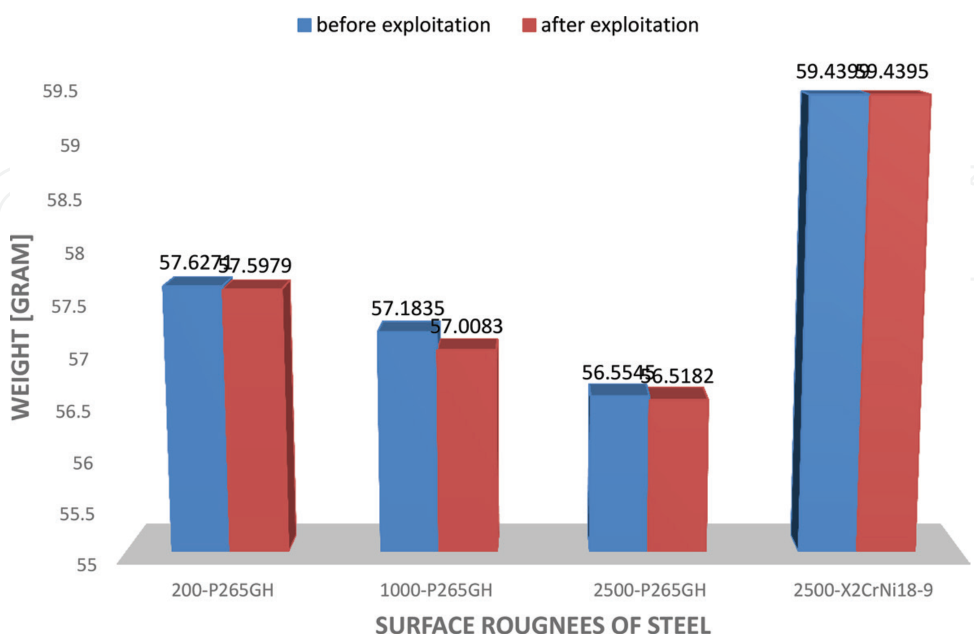

Figure 5. Loss of mass, i.e. the mass of cavitation generator made of P265GH and X2CrNi18-9 (304L) steel after use in cavitation wear conditions in a continuous flow blast machine in a closed cycle [6].

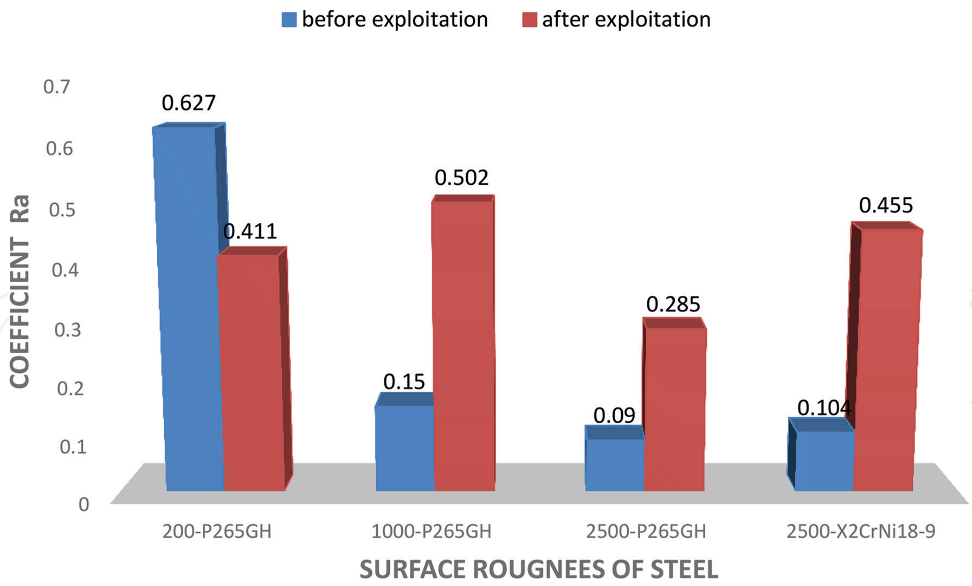

Figure 6. Variation of the surface roughness coefficient R_a of cavitation generators made of P265GH and X2CrNi18-9 (304L) steel after use in cavitation wear conditions in a continuous flow blast machine in a closed cycle [6].

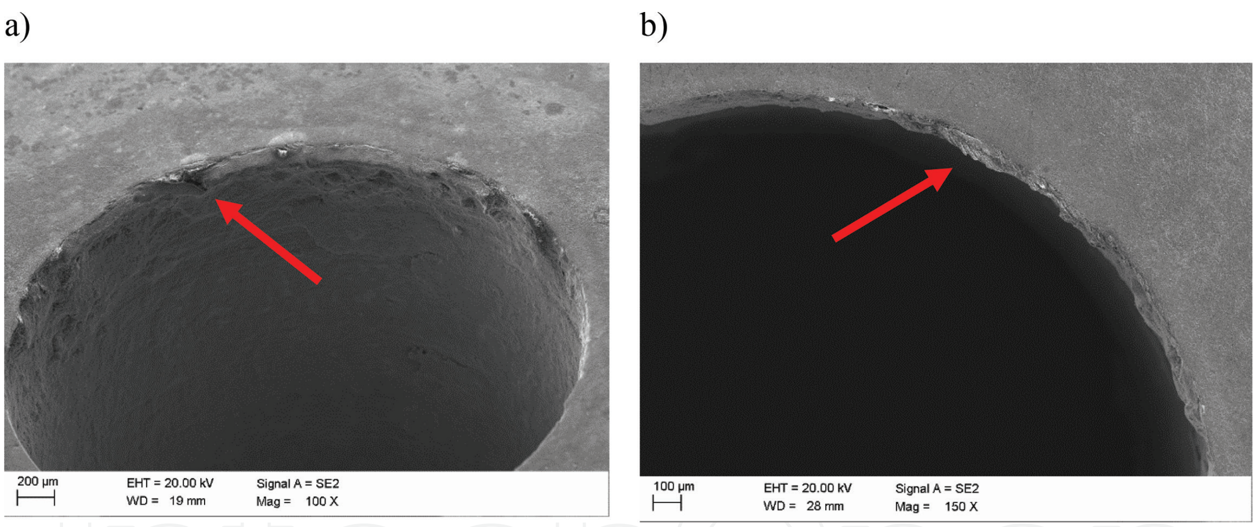

Figure 7. Result of cavitation wear of the surface of a constructional element made of P265GH steel after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 100×; (b) magnification of 150×.

decreases the roughness class from 10th to 8th. A small mass loss from 56.5545 to 56.5182 g and roughness factor growth from 0.09 to 0.285, i.e. fall from 10th to 9th roughness class, was seen for the last cavitation generator made of ferritic-pearlitic steel, designated as 2500-P265GH, operated for 500 PMHs.

Far better results were achieved for a constructional element such as a cavitation generator made of austenitic X2CrNi18-9 (304L) steel, wet sanded with sandpaper with the grain size of 2500, with the weight of 59.4399 g and with the surface roughness factor R_a of 0.1, which is grouped in the 10th roughness class. The weight dropped to only 0.0002 g after operation, i.e. it was within the measurement error range, and the roughness factor rose to 0.455, which ranks it in the 8th roughness class [6].

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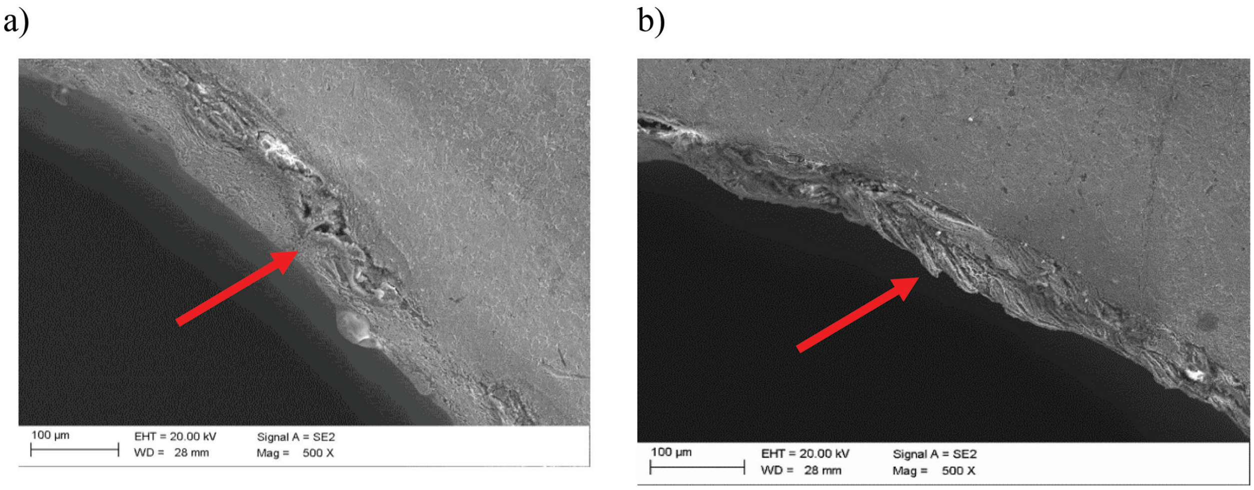

Figure 8. Result of cavitation wear of the surface of a constructional element made of P265GH steel after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a and b) magnification of 500× [6].

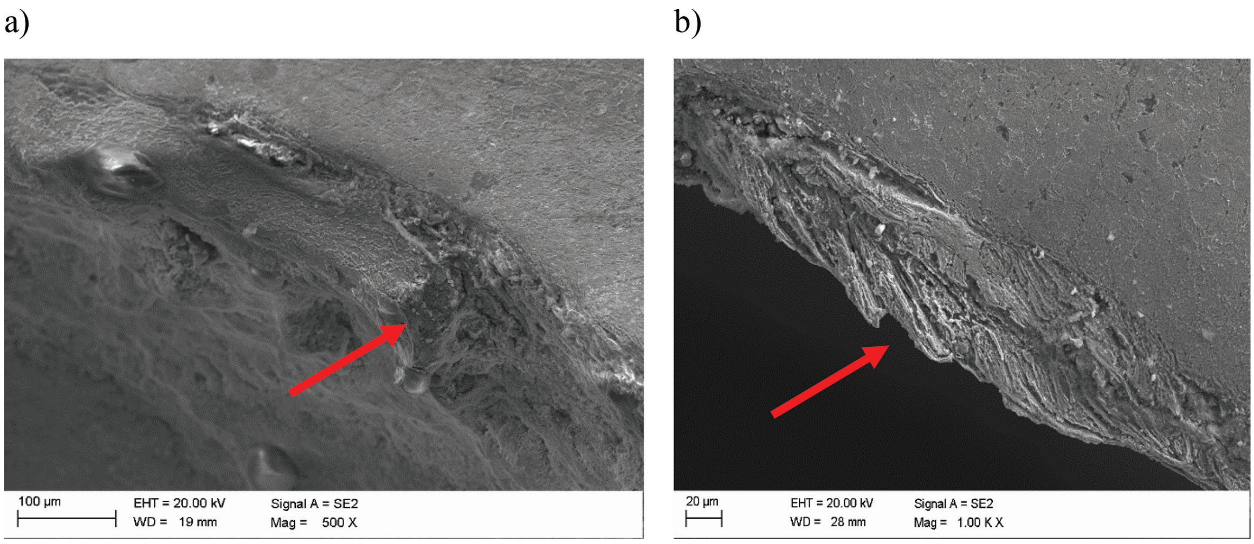

Figure 9. Result of cavitation wear of the surface of a constructional element made of P265GH steel after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 500× and (b) magnification of 1000×.

It was also confirmed on the basis of macroscopic examinations undertaken using a scanning electron microscope for a constructional element such as a cavitation generator made of P265GH steel, designated as 2500-P265GH, that numerous places exist on the edges of straight-through openings, especially on the edges with the biggest opening area in the central part of the cavitation generator, which were rounded by the flowing water (**Figure 7**). Cavitation craters and pits were formed in the first stage, then such craters were piling up and successive centres of cavitation wear were being formed, leading to either complete damage and breaking of the material part from the edge or to the material flowing towards the opening interior according to the medium flow direction (**Figures 8** and **9**). It was noticed for magnifications of 500–2000× that the surface of the cavitation generator made of P265GH steel bears traces of intensive wear in the form of irregularly spaced pits and craters and clusters of surface degradation of the constructional elements created in operation lasting 500 PMHs in a cavitation environment (**Figure 10**) [6].

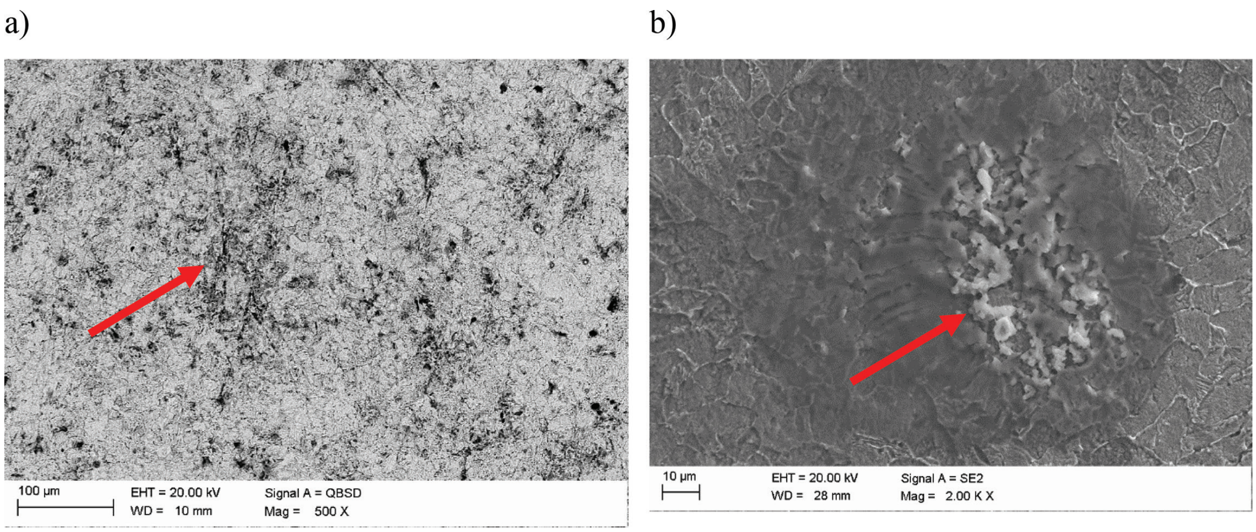

Figure 10. Result of cavitation wear of the surface of a constructional element made of P265GH steel after operation in a stream and flow device (**Figure 2a**) for (a) magnification of 500× and (b) magnification of 2000×.

4. Results of physical simulations of cavitation generators with WC/C protective coating

Surface engineering is a field of materials engineering enjoying one of the highest growth rates, distinctive by the fact that a core (substrate) material of the engineering element is frequently subjected to such procedures as heat treatment, thermochemical treatment or others which thus have influence on a marked improvement of mechanical properties of the engineering material surface. Given the multiple techniques enabling to improve the strength of the surface of engineering materials used for elements in a machine working in difficult cavitation environment conditions, two coating deposition methods play an important role in industrial practice, namely: physical vapour deposition (PVD) or its variants such as xxPVD (e.g.: PAPVD, LAPVD) and chemical vapour deposition (CVD) or its variants such as xxCVD (e.g.: APCVD, LPCVD).

A modern thermochemical treatment technology such as PVD deposition onto a material surface is distinct for a coating deposition process using ionised plasma where vapours of the given material crystallise on the surface of the treated substrate. The material which is subject to PVD treatment is enhancing mechanical parameters considerably and its strength properties are also additionally improved, being the whole constructional element or just part of it. Such modern surface engineering technologies enable to dedicate a metallic material, which was previously not considered for use as a constructional element due to its reduced useful properties. In addition, by implementing such technology as PVD onto the material surface, the constructional materials being the substrate (core) can be used more widely, with such materials having until now medium or insufficient mechanical properties. Such technology of 'enhancement' with a composite coating or layer exceeds by far the strength parameters of the given constructional element's core. The methods of depositing composite coatings or layers onto metallic cores (substrate) were also applied to improve the strength and life of constructional elements used in a cavitation environment.

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It is very important is to describe a correlation between technologies of deposition of PVD coatings consisting of composite layers and their strength and mechanical-fatigue properties as well as the way of their degradation caused by a cavitation environment. The strength properties of coatings deposited by PVD methods are highly appreciated in mechanical terms and are dedicated at the same time to such branches of industry as: power, heating, aviation, automotive, railway, chemical, petroleum, gas, river and maritime sector. For this reason, elements of machines and devices are becoming more and more popular, which are made of non-alloy and low-alloy steels enhanced through various types of surface treatment, whereas a given project's economy and budget are naturally the main argument for such design. The coatings deposited by PVD are distinct for their high hardness, resistance to oxidisation, a low friction coefficient and antiwear and anticorrosion properties. Because most of industrial machines and devices are exposed in their work to impact and fatigue loads working in a variable cycle, the knowledge of PVD coatings degradation mechanisms under a dynamic load is especially important. PVD technologies have been used successfully as coatings resistant to wear deposited onto the surface of constructional materials.

PVD coatings significantly improve the impact and fatigue strength and resistance to cavitation wear. A disadvantage of hard coatings is that they crack easily in the brittle and cracking mode during use in extreme environments. A mechanical behaviour of coatings depends on which degradation mechanism dominates during deformation in a given operational environment. A degradation mechanism is connected with a PVD coating's structure, namely: morphology, phase composition, number of components of individual layers, number of coatings, thickness of individual coatings and total thickness of coatings. Moreover, a coating degradation mechanism is dictated by mechanical properties such as: Young's modulus, hardness and adhesion, as well as by the substrate's (core's) properties and the frequency of external interactions linked directly to the working environment. Multilayer (composite) or monolayer (single) coatings are produced to achieve a coating with special properties [7].

A special low-friction tungsten carbide (WC/C) coating, applied by the PVD technique, was deposited to improve functional properties, tested in a cavitation environment, for 500 PMHs in an independently designed and fabricated author's stream and cavitation device, where cavitation generators made of P265GH and X2CrNi18-9 steel were implemented. Mass and surface roughness were measured and microscope examinations were carried out before and after use in a stream and flow device, operated continuously in a closed cycle (**Figure 2**), to identify the degree of wear of the cavitation generators with a WC/C coating applied. **Figure 11** shows a representative image of a cavitation generator with a special low-friction tungsten carbide (WC/C) coating deposited by PVD onto a P265GH steel substrate. It was found, with an analysis made in several points of the sample, that the average coating thickness is 1.55 μm.

Constructional elements such as cavitation generators with a WC/C coating deposited were operated for 500 PMHs in a stream and flow device generating a cavitation environment in continuous operation in a closed cycle. The constructional elements with a PVD coating were examined after prior cleaning in an ultrasonic cleaner, and then weighed on an analytical scale, AS/X by RADWAG. Surface roughness was determined with a Surtronic 25 contact profilometer by Taylor Hobson. At least four measurements, along the length of 16 mm, in different areas of the cavitation generator surface with a PVD coating, were made to determine surface roughness of each constructional element.

The results of examinations of mass and surface roughness measurements of cavitation generators with a PVD coating are shown, respectively, in **Figures 12** and **13**.

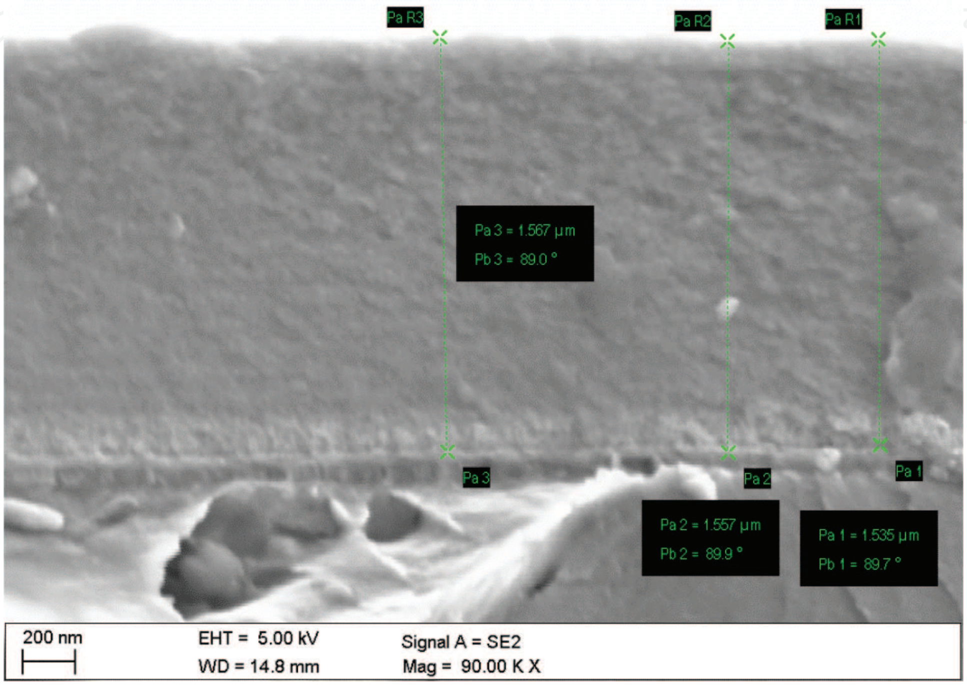

Figure 11. Cavitation generator fracture with visible WC/C coating deposited by PVD with coating thickness of 1.55 µm onto P265GH steel substrate.

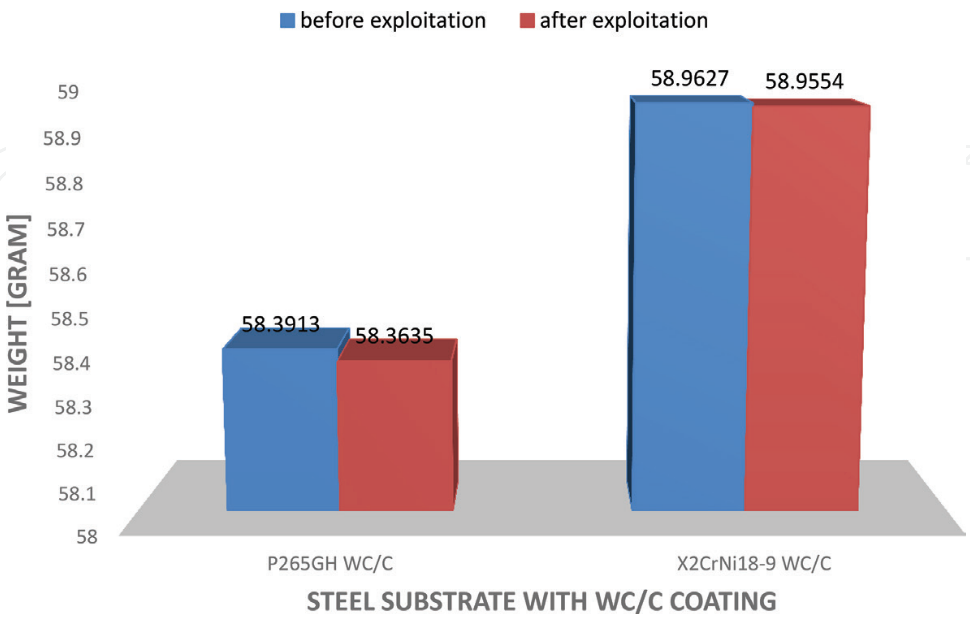

Figure 12. Loss of mass of cavitation generator made of P265GH and X2CrNi18-9 (304L) steel with a WC/C coating deposited by PVD after use in cavitation wear conditions in a continuous flow blast machine in a closed cycle [6].

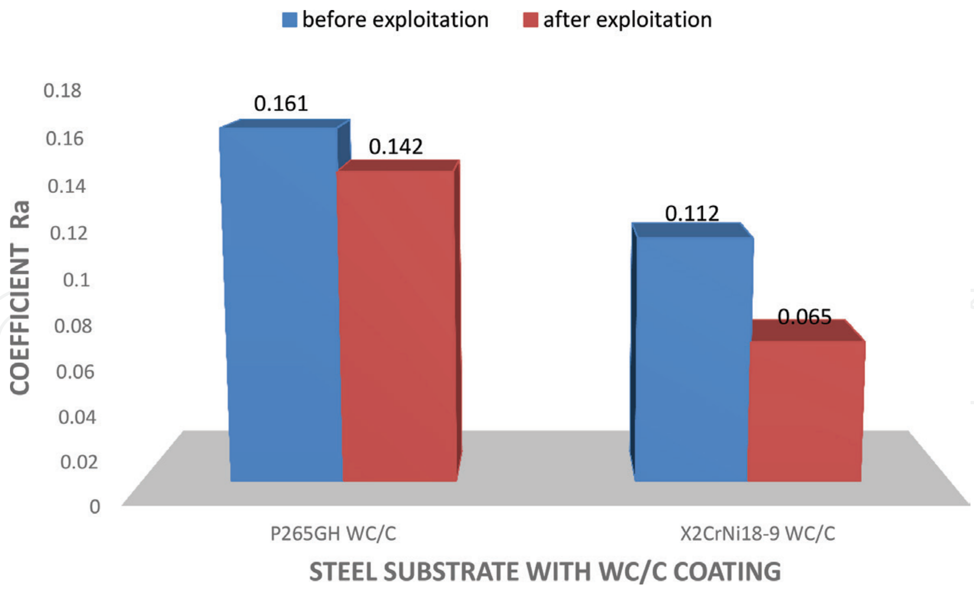

Figure 13. Variation of the surface roughness coefficient R_a of cavitation generators made of P265GH and X2CrNi18-9 (304L) steel with a WC/C coating deposited by PVD after use in cavitation wear conditions in a continuous flow blast machine in a closed cycle [6].

A cavitation generator with a ferritic-pearlitic substrate structure (P265GH) with a WC/C coating applied before use, weighed 58.3913 g before use and had a surface roughness factor R_a of 0,161, thus falling to the 10th surface roughness class. A mass loss of approx. 0.03 g was identified as a result of operation for 500 PMHs and a roughness factor R_a fell from 0.161 to 0.142 (**Figures 12** and **13**).

On the other hand, the other generator with an austenitic substrate structure (X2CrNi18-9) with a WC/C coating, operated in a stream and flow device, had the weight of 58.9554, losing only about 0.01 g during operation (**Figure 12**). The highest decrease of the roughness factor R_a from 0.112 to 0.065 (**Figure 13**) was seen for this generator, hence its roughness class was changed from 10th to 11th acc. to PN-EN ISO 1302:2004.

In order to verify the obtained wear results, cavitation generators made of P265GH and X2CrNi18-9 (304L) steel with a WC/C coating deposited by PVD after operation in a stream and flow device in continuous operation in a closed cycle for 500 PMHs were examined in a modern contactless profilometer, Profilm3D, by Filmetrics. This innovative measuring device serves, among others, to examine a profile of the examined material's surface topography and roughness and to measure the coating thickness by comparing a layer of the uncoated substrate with the height of the given coating with the accuracy of up to 1 nm [8].

The aim of contactless examinations with a profilometer was to determine the topography profile for the part of the surface of the constructional element working in a cavitation wear environment. The part of the cavitation generator was examined as a first featuring a ferritic-pearlitic substrate structure (P265GH) with a protective WC/C coating, which had the biggest material loss in the area of the generator's straight-through openings. A change of the profile shape at the measuring distance of 600 μm, directed towards the cavitation generator's straight-through opening, was found by analysing the profile. It is seen that the profile was lowered by about 10 μm with the physical measuring distance of 400 μm towards the opening. The results were confirmed for several tested straight-through openings of the cavitation generator. A very steep cavitation wear profile was identified in some of the tested areas near the straight-through openings, with visible parallel faults and grooves on its end being a destroyed edge of the constructional element's working opening, the result of which was a medium (water) flowing perpendicular to the direction of visible damages of the cavitation generator. A surface in the examined part of the generator had single and few craters and pits resulting from the cavitation processes the constructional element was subject to for 500 PMHs (**Figure 14**).

Much smaller roundings of edges of working openings, at the same time with a steep profile of surface wear according to the water (medium) flow direction, were found for a cavitation generator made of austenitic X2CrNi18-9 steel with a WC/C coating, where the profile height difference was approx. 4 μm over a measuring distance of 850 μm for a physical measuring distance of ~560 μm. Moreover, numerous local pits and craters with a small volume were noticed, especially in the nearest surrounding of the straight-through openings, created as a result of use for 500 PMHs in a stream and flow device generating a cavitation environment in continuous operation in a closed cycle (**Figure 15**).

An imaging technique with a confocal microscope was applied to confirm the results (**Figures 14** and **15**) obtained with an optical profilometer, Profilm3D, by Filmetrics. Confocal microscopy is used, in particular, for examination of: materials surface topography, to identify microstructure and material surface defects and for precise measurements with a higher quality of imaging. Confocal microscopy is a modification of light microscopy featuring higher contrast, higher depth of sharpness and resolution capacity, where a narrow source of light is used in the form of a laser radiation beam, owing to which an image is achieved with large power concentrated in a given test point. An advantage of this measuring technique is that the tested samples are visualised, 3D and 4D images are reconstructed, and a series of optical sections are recorded at the different depth of the preparation, as well as high image resolution [9].

Cavitation generators made of P265GH and X2CrNi18-9 (304L) steel with a (WC/C) tungsten carbide coating deposited, subjected to operation for 500 PMHs in a cavitation wear environment,

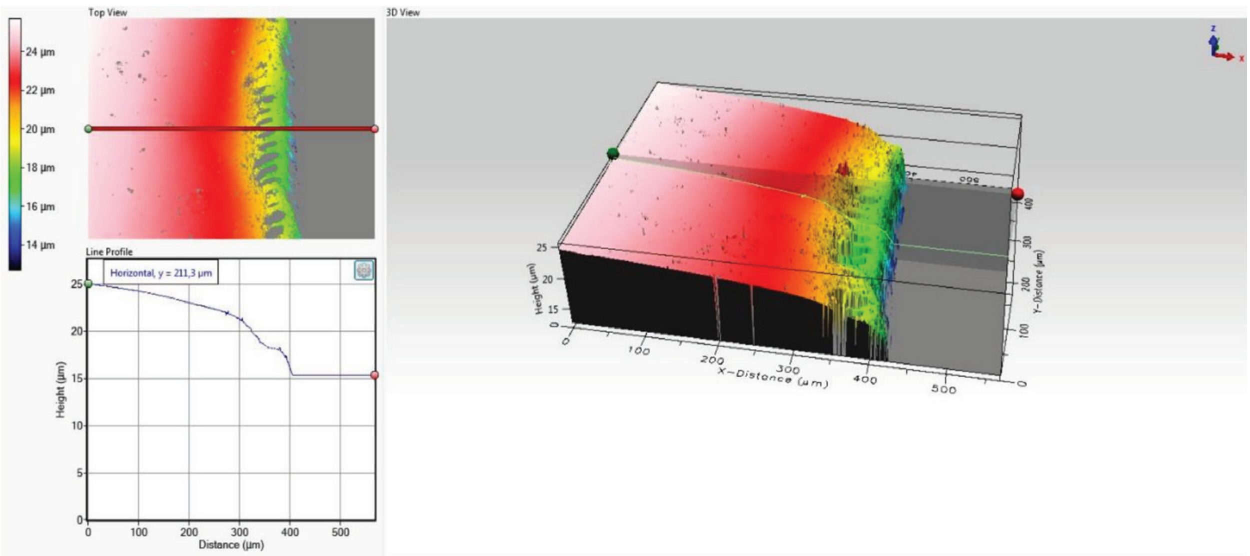

Figure 14. Topography profile of cavitation wear of part of the surface and working opening of the P265GH cavitation generator with protective WC/C coating after operation for 500 PMHs.

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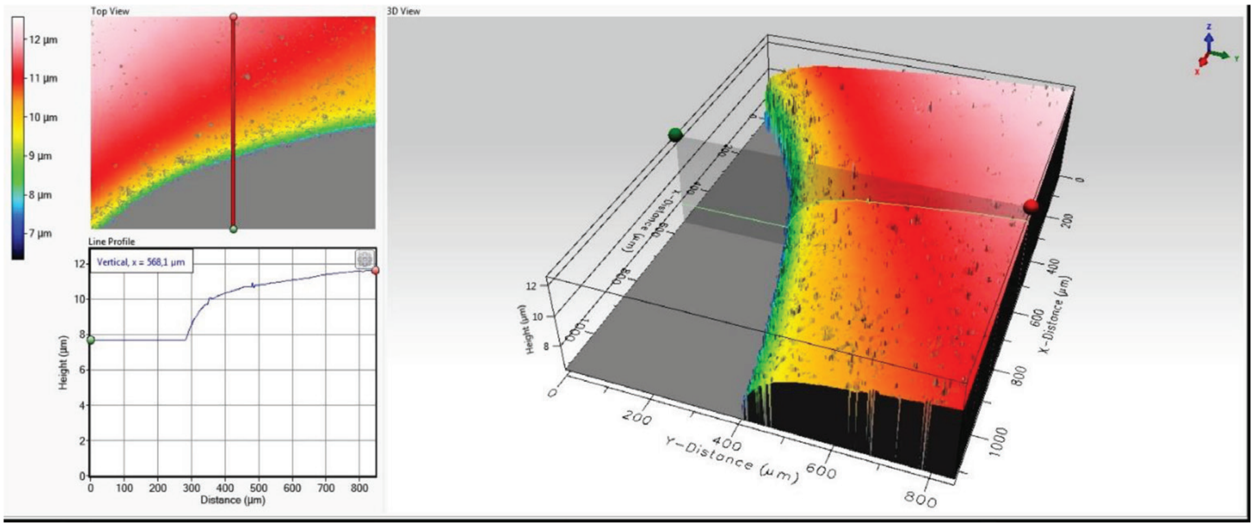

Figure 15. Topography profile of cavitation wear of part of the surface and working opening of the X2CrNi18-9 cavitation generator with protective WC/C coating after operation for 500 PMHs.

were examined with a Laser Scanning Microscope, LSM 5 Exciter, by Zeiss. The examinations were carried out with a diode laser with a wavelength of 450 nm. A cavitation generator made of P265GH steel, with a WC/C coating deposited, was characterised by a profile height difference of the examined surface of 5.7 µm along the measuring distance of 130 µm, with a physical measuring distance of 86 µm, whereas a very steep and brittle character of cavitation wear of the working opening edge was noticed, the effect which was an intensively flowing medium (water). The uneven wear of the opening edge was also observed, as a gentle parabolic shape of the edge or as a sharp crack, detachment of part of the constructional element's material (**Figure 16**).

However, a cavitation generator made of X2CrNi18-9 steel, with a WC/C coating deposited, was characterised by a profile height difference of the examined surface of 12.7 µm along the measuring distance of 130 µm, with a physical measuring distance of 82 µm. An extensive strip of material loss was found for the examined sample area, based on which it can be concluded that the deposited coating was detached from the substrate material in a brittle way, whereas the process of rounding and a non-homogeneous profile of the material edge results from the intensively flowing medium (water) towards the inside of the constructional element's working opening (**Figure 17**).

Over the next stage of structural examinations, cavitation generators made of P265GH and X2CrNi18-9 steels with a monolayer protective WC/C coating deposited by the PVD technique, subjected to operation in a stream and flow device in continuous operation in a closed cycle for 500 PMHs, underwent a macroscopic analysis using a scanning electron microscope, SUPRA 35, with secondary electrons (SE) detection. The results of the examinations are presented in **Figures 18–21**. Numerous fatigue and flow processes were found for cavitation generators made of P265GH steel with a protective WC/C coating, subjected to operation in a stream and flow device for 500 PMHs, where the flowing water (medium) was destroying the coating surface in the form of incised bands (**Figures 18a** and **19a**) towards the inside of the working opening (orange arrow). The coming cavitating water caused considerable destructions as a result of which the coating cracked and collapsed (red arrow), developing oblong craters with a different height on the analysed part of the constructional element's

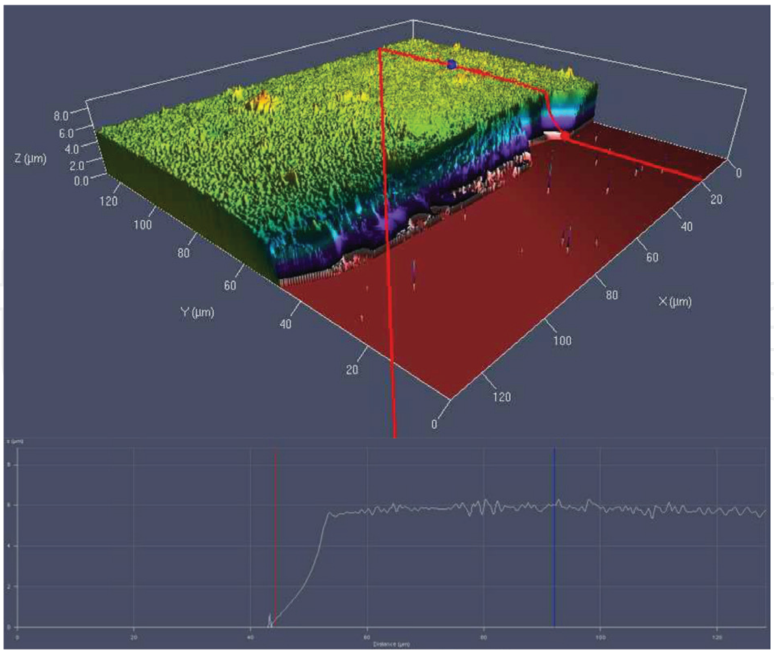

Figure 16. Topography profile of cavitation wear of part of the surface and working opening of the P265GH cavitation generator with protective WC/C coating after operation for 500 PMHs.

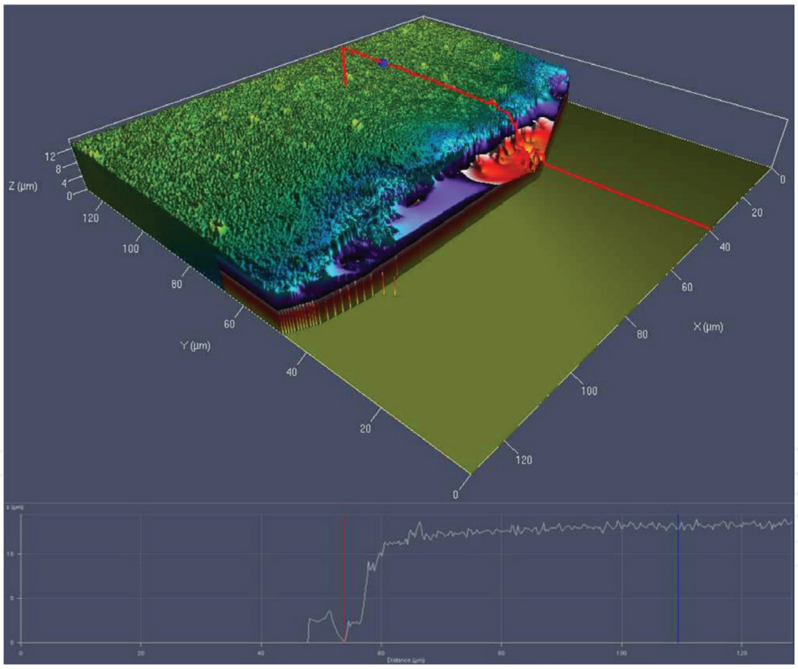

Figure 17. Topography profile of cavitation wear of part of the surface and working opening of the X2CrNi18-9 cavitation generator with protective WC/C coating after operation for 500 PMHs.

part. Numerous void places (cavities) were observed in **Figures 18** and **19** (yellow arrow) due to removing the droplets of the deposited carbides as a result of operation in a cavitation environment for 500 PMHs. Additionally, a brittle mechanism of WC/C coating cracking was noticed, characterised by being situated in parallel to the edge of the constructional element's working opening, where destruction was initiated near the edges of the infused or removed tungsten carbides (blue arrow) (**Figure 19b**).

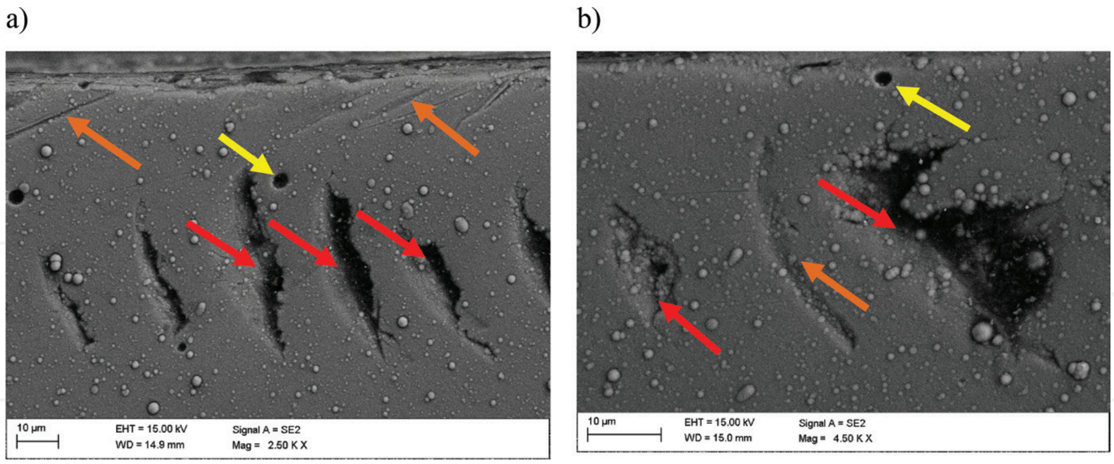

Figure 18. Result of cavitation wear of the surface of a constructional element made of P265GH steel with a WC/C coating deposited by PVD after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 2500× and (b) magnification of 4500×.

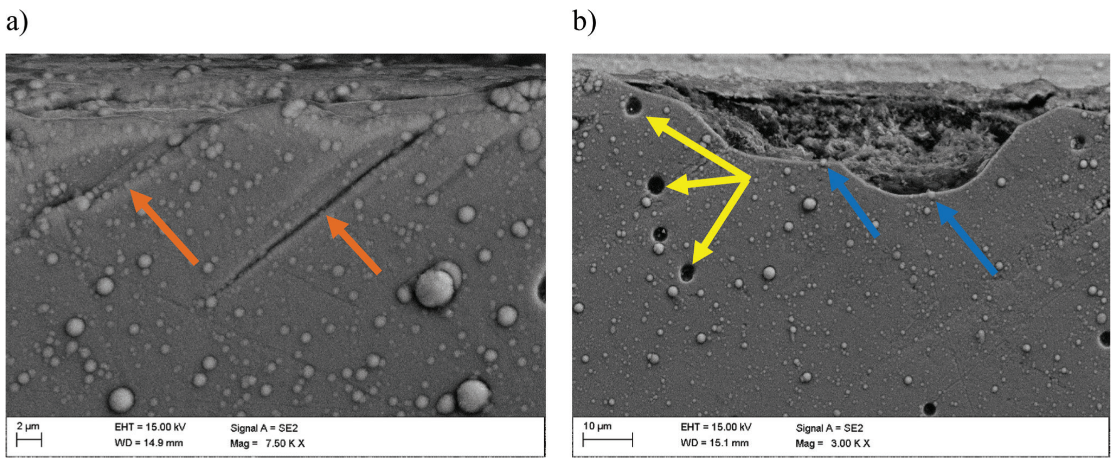

Figure 19. Result of cavitation wear of the surface of a constructional element made of P265GH steel with a WC/C coating deposited by PVD after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 7500× and (b) magnification of 3000×.

Long, axial coating detachment and delamination towards the working opening edge (green arrow) was identified in case of cavitation generators made of X2CrNi18-9 steel with an austenitic substrate structure with a WC/C coating deposited by PVD and operated in the conditions of cavitation wear. An area of cavitation wear with a polygonal shape with a different height from the plane of the constructional element (green arrow) and void places (cavities) after the removed tungsten carbides on the examined piece of the constructional element's area (yellow arrow) were also observed (**Figure 20a** and **b**). Cavitation wear effects were also found near straight-through openings in the form of brittle cracks and delamination as a mesh of the WC/C coating implemented in several places of the tested sample on a large area. The cracked coating was moving during operation towards the working opening, which can be signified by even gaps between particular plates of the WC/C coating, until the coating is completely detached from the substrate material and its larger parts falls apart due to activity of the medium under high pressure (violet arrow) (**Figure 21a**). Another degradation mechanism of part of the cavitation generator's surface in the operation process over the time of

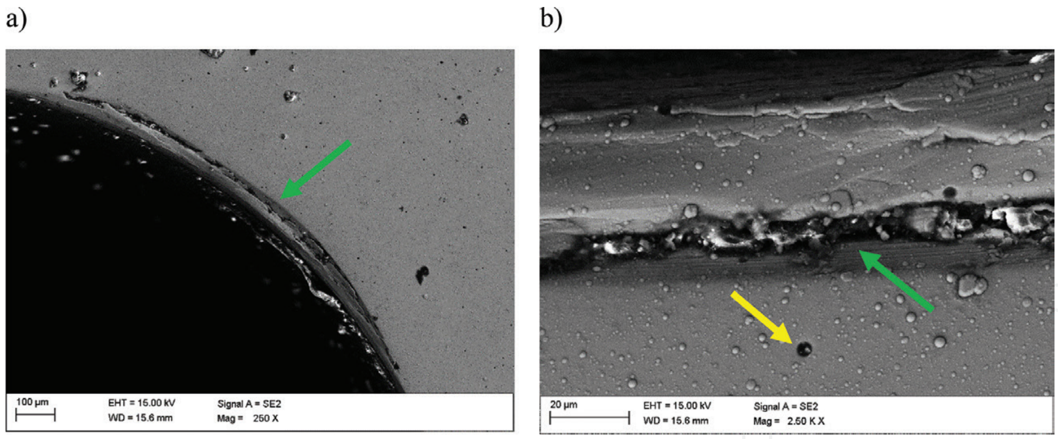

Figure 20. Result of cavitation wear of the surface of a constructional element made of X2CrNi18-9 steel with a WC/C coating deposited by PVD after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 250× and (b) magnification of 2500×.

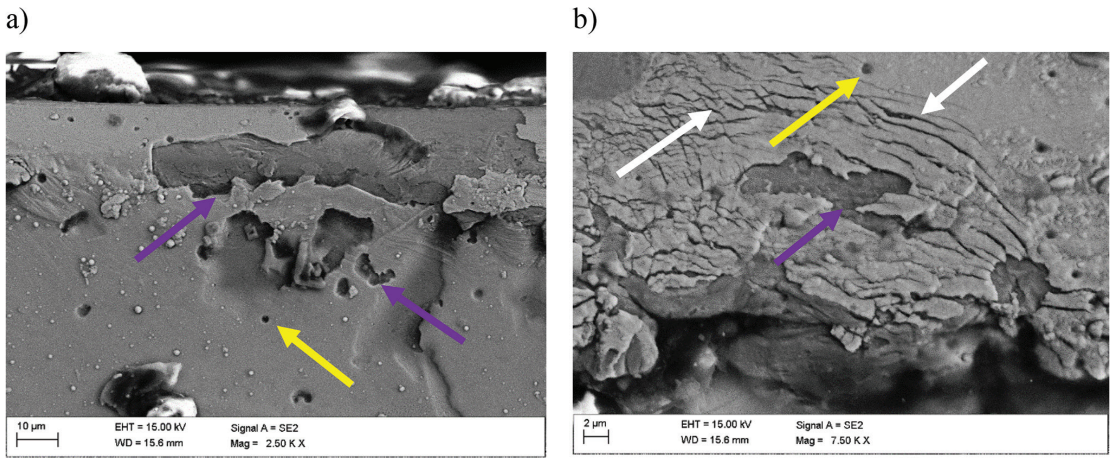

Figure 21. Result of cavitation wear of the surface of a constructional element made of X2CrNi18-9 steel with a WC/C coating deposited by PVD after operation in a stream and flow device (**Figure 2a**) for 500 PMHs: (a) magnification of 2500× and (b) magnification of 7500×.

500 PMHs were fatigue processes caused by long-term interaction of the cavitation environment, the result of which was the plastic waving of the substrate material (white arrow) made of X2CrNi18-9 steel, which also led to its significant destruction, cracking of the WC/C coating and consequently to its detachment from the substrate (**Figure 21b**).

5. Summary

The following conclusions were drawn based on the experiments carried out in an author's stream and flow device generating a cavitation environment in continuous operation in a closed cycle for 500 PMHs and based on the examinations of cavitation generators with and without a protective coating:

1. The highest mass loss of 0.1752 g was seen for a cavitation generator made of ferritic-pearlitic P265GH steel, wet sanded with sandpaper with the grain size of 1000, where the

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biggest cavitation wear effects were also noticed, confirmed with photographs from an electron scanning microscope.

2. The smallest mass loss with its value at the level of a measurement error was recorded for a cavitation generator made of austenitic X2CrNi18-9 (304L) steel, sanded with sandpaper with the grain size of 2500, however, significant cavitation wear was recorded on its surface in form of axial brittle cracks inside the material, initiated towards the edges of the working opening.

3. The roughness factor Ra was greatly reduced for a constructional element made of P265GH steel with a ferritic-pearlitic structure with a high surface roughness factor Ra in the initial condition after a process in a cavitation environment for 500 PMHs. It can be concluded that such a process (surface smoothing) may concern a majority of engineering materials which would be subjected to operation in a cavitation environment.

4. The cavitation generators featuring a low surface roughness factor Ra in the initial state have increased - as a result of the impact of the cavitation environment - the roughness factor Ra regardless the steel structure, either ferritic-pearlitic P265GH or austenitic X2CrNi18-9 steel.

5. The deposition of a monolayer protective WC/C coating onto constructional elements which were subjected to wear in a cavitation environment for 500 PMHs did not prevent the mass loss of cavitation generators with a ferritic-pearlitic P265GH structure and austenitic X2CrNi18-9 structure, however, it significantly slowed down this process (by referring to cavitation generators without a coating at least four times).

6. The surface roughness factor Ra of cavitation generators, onto which a WC/C coating was deposited, subjected to operation in a cavitation environment for 500 PMHs, fell independently from the substrate applied, onto which a coating was deposited.

7. Topography examinations of the surface of constructional elements onto which a WC/C coating was deposited, using a modern contactless profilometer and a confocal microscope with the CLSM technique, have revealed extensive cavitation wear of the surface, especially near the edge of the cavitation generator's working opening regardless the substrate material.

8. A monolayer WC/C coating deposited on P265GH steel was wearing in a cavitation environment in a distinctive manner by collapsing parallel to the direction of the flowing water and by brittle cracking of the coating on the edge of the working opening.

9. A surface of a constructional element in the form of tungsten carbide, deposited on X2CrNi18-9 steel, was wearing during operation in a cavitation environment for 500 PMHs with coating flakes detaching with a brittle cracking mechanism and with plastic wear of the substrate in the form of substrate waving due to a fatigue-cyclic character of the working environment.

10. The tests results obtained allow to conclude that the application of special low-friction protective coatings allows to reduce costs associated with selection of engineering materials for a substrate of constructional elements working in a cavitation wear environment. P265GH steel is 4 times cheaper than austenitic chromium-nickel X2CrNi18-9 steel, and if a WC/C coating is deposited in this case, this considerably extends the working time of such elements in a cavitation environment.

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