

EVALUATION OF MICROSCOPIC DEFECTS IN HYDRAULIC TURBINE BLADE COATINGS

ОЦІНКА МІКРОСКОПІЧНИХ ДЕФЕКТІВ ПОКРИТТЯ ЛОПАТОК ГІДРОТУРБІН

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Hydro-abrasive wear is a major problem for the efficiency and durability of Francis turbines, widely used in hydroelectric power plants due to their ability to transform hydraulic energy into sustainable electricity. Constantly exposed to abrasive particles in water, turbine components are subjected to intense stresses, which lead to progressive deterioration and shortening of their lifespan. In this context, scanning electron microscopy (SEM) analysis becomes an essential tool for the evaluation and understanding of microscopic defects induced by hydro-abrasive wear. SEM allows for the detailed characterization of the affected surfaces and the identification of the types of damage, thus providing fundamental data for the optimization and selection of abrasion-resistant materials. Thermal spray of materials, such as Metco 71VF-NS (WC12Co) are an important solution in combating wear, being renowned for their increased hardness and strength. These sprayed layers not only protect the turbines from the effects of hydro-abrasive wear, but also contribute to the overall efficiency of the system by reducing the frequency of repairs and maintenance. Thus, in the context of renewable energy, where reliability and durability of equipment are essential, the use of advanced materials to protect Francis turbines represents a crucial step towards sustainable and efficient production of electricity based on hydraulic resources. 22 Ref., 2 Tabl., 5 Fig.

Keywords: thermal spraying, coatings, SEM, structure, thickness, porosity

Гідроабразивне зношування є основною проблемою ефективної та довговічної роботи турбін Френсіса, які широко використовуються на гідроелектростанціях завдяки їхній здатності перетворювати гідравлічну енергію в стабільну електроенергію. Постійно піддаючись впливу абразивних частинок у воді, компоненти турбіни зазнають інтенсивних навантажень, що призводить до прогресуючого псування та скорочення терміну їх служби. У цьому контексті аналіз за допомогою скануючої електронної мікроскопії (SEM) стає важливим інструментом для оцінки та розуміння мікроскопічних дефектів, викликаних гідроабразивним зносом. SEM дозволяє детально охарактеризувати уражені поверхні та ідентифікувати типи пошкоджень, таким чином забезпечуючи фундаментальні дані для оптимізації та вибору матеріалів, стійких до стирання. Терморозпилення матеріалів, таких як Metco 71VF-NS (WC12Co), є важливим рішенням у боротьбі зі зносом, відомим своєю підвищеною твердістю та міцністю. Ці напилені шари не тільки захищають турбіни від впливу гідроабразивного зносу, але й сприяють загальній ефективності системи, зменшуючи частоту ремонтів і технічного обслуговування. Таким чином, у контексті відновлюваної енергетики, де надійність і довговічність обладнання є важливими, використання передових матеріалів для захисту турбін Френсіса є вирішальним кроком до сталого та ефективного виробництва електроенергії на основі гідравлічних ресурсів. Бібліогр. 22, табл. 2, рис. 5.

Ключові слова: термічне напилення, покриття, скануюча електронна мікроскопія, структура, товщина, пористість

1. Introduction. Choosing the right turbine for a specific application requires a detailed analysis of design parameters, including energy efficiency, wear resistance and operating conditions. Therefore, combining advanced materials analysis technologies with efficient design solutions contributes to the development of Francis turbines that not only optimize energy production but also minimize environmental impact, thus supporting the transition to a more sustainable and greener energy system.

Turbine blades are the most affected by hydro-abrasive wear, being directly exposed to the water stream and abrasive particles [1–3]. Wear can significantly reduce the operational efficiency of the turbine, as the affected surfaces become rougher and turbulence increases, leading to energy losses.

A high concentration of sand, gravel or other particles can accelerate wear. In regions where rivers carry large amounts of sediment, turbine wear is particularly severe, and hard materials such as quartz cause

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faster wear than soft particles [1, 4]. Water velocity can influence hydro-abrasive wear; higher water velocity means that suspended abrasive particles have greater kinetic energy and can cause faster wear.

Modernization of existing plants, development of advanced turbine technologies, and efficient water management are essential to maintaining the important role of this form of energy. An increase in the integration of hydropower with other renewable sources, such as solar and wind, is expected to ensure a stable energy supply. Investments in pumped storage technology and the development of marine energy also open up new possibilities for the future of hydropower.

There are known a lot of nondestructive (NDT) techniques possible to solve the diagnostic problems related with protective layers of the gas turbine components and blades operated in hard conditions [5–13]. In [6–7] eddy current (EC) NDT techniques for detection of magnetic anomalies in gas turbine disks and flaws located in fillet zone of blade were proposed and investigated. The promising results were obtained by apparatus realized by so called frequency scanning eddy current (EC) technique developed in CESI S.p.A. (Milan, Italy [8–10]. This EC technique based on the evaluation of EC probe impedance changes in the 5.9 to 8 MHz range of operational frequencies was used to characterize the depths of grinding burns in heat resistant steel in the range of depths from 1...3 to 100 μm [11]. In this paper, the second EC method based on elevated 200 MHz operational frequency application was successfully applied also. The EC technique based elevated frequencies of 100 MHz, 200 MHz and 400 MHz application was successfully applied for evaluation of parameters of gas-filled layer in titanic allow blades [12–13].

In this paper, the base material and hard layer structures of turbine blades were analyzed as the first stage needed to solve the related diagnostic problems.

2. Materials and method of thermal spraying.

Base materials. AISI 4140 stainless steel is a stainless steel used for making hydraulic vanes, due to the balance between cost and performance. It is resistant to corrosion in many corrosive environments. This steel can be subjected to high mechanical loads, being strong enough to withstand impact forces. Hydraulic vanes made of this steel ensure a relatively long service life.

Figure 1 shows an acicular martensitic microstructure obtained under an optical microscope. This microstructure is formed as a result of the carbon content and the applied heat treatments, such as quenching and tempering. During the quenching process, the steel is heated to a high temperature, followed by rapid cooling, which leads to the transformation of aus-

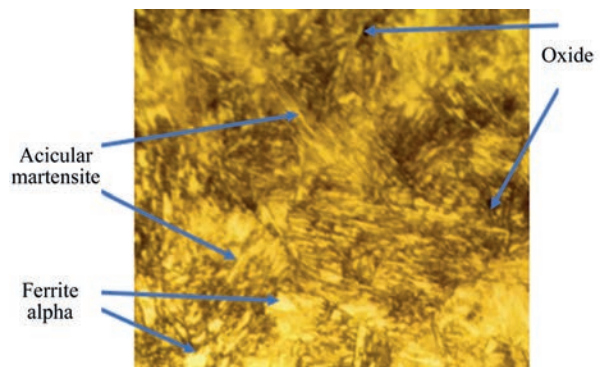


Figure 1. Microscopic structure of AISI 4140 stainless steel
Рис. 1. Мікроструктура нержавкої сталі AISI 4140

tenite into martensite [14, 15]. This transformation process produces a network of long and thin needles, oriented in various directions, which are visible at the microscopic level and give the steel superior mechanical properties, such as hardness and increased resistance to mechanical stress.

The acicular martensitic structure plays an important role in the mechanical behaviour of AISI 4140 steel, as it provides wear resistance and the ability to take on high loads without permanent deformation. Tempering treatments also allow the reduction of internal stresses and improvement of the ductility of the steel, while maintaining good mechanical strength. In conclusion, the acicular microstructure of martensite is a key factor in ensuring the performance of this type of steel in demanding industrial applications [16, 17].

Due to the exposure of this sample to corrosive environments (it was taken from a decommissioned Francis turbine), the appearance of oxides on the surface or in the microstructure is observed, visible as dark spots or inclusions under the microscope. These can slightly affect the behaviour of the material under certain conditions. It can also be observed that areas with alpha ferrite, a more ductile phase that forms during solidification, also appear. Alpha ferrite appears in the form of elongated grains dispersed among the martensite needles. These grains contribute to reducing the brittleness and increasing the ductility of steel.

Coating Thermal Spray Method. Plasma jet spraying is an advanced coating method that applies hard coatings to metallic, ceramic, or composite substrates to improve their functional properties [18, 19]. This technology is commonly used to add wear, hydro-abrasion, high temperature, and corrosion resistance using materials such as WC12Co and ceramic oxides. The process involves generating a plasma jet through an electric arc, which heats a working gas (argon, hydrogen, helium) to temperatures up to 15 000°C.

Plasma jet spraying is an advanced, versatile, and efficient technology for applying hard coatings, such as WC12Co (Figure 2). This technology provides

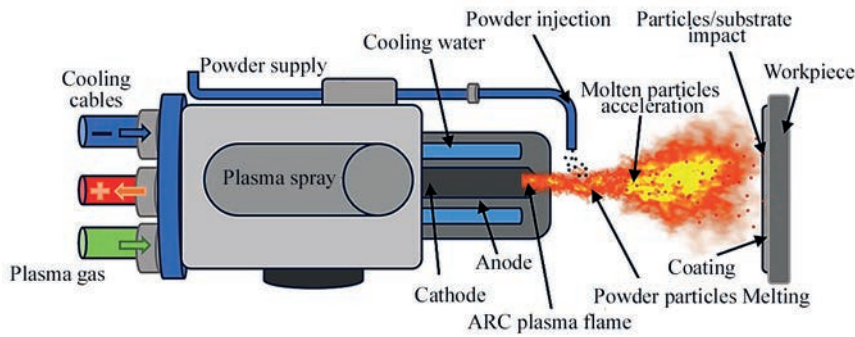


Figure 2. Plasma jet thermal spraying
Рис. 2. Термічне напilenня плазмовим струменем

films with superior wear, corrosion, and high temperature resistance properties, making it essential in various industries where surface protection is critical for performance and durability [20].

Plasma is an ionized gas capable of carrying the energy needed to melt the material powder particles injected into the plasma flow. Plasma jet spraying produces dense and highly adherent layers due to the high impact velocity of the molten particles and the high temperature of the plasma.

Spraying Material. Plasma-sprayed coatings are used in critical industries such as aerospace, automotive, and energy. In particular, coatings WC are highly valued for their high hardness and wear resistance, and are used to protect surfaces subjected to extreme conditions such as cutting tools, components subject to intense erosion and friction, or equipment parts exposed to abrasive environments [21].

To spray the coating by plasma thermal spraying WC12Co powder combined with a cobalt binder. This mixture provides excellent wear, erosion, and shock resistance, and is widely used for applications requiring extreme durability in abrasive environments [22].

3. Results and Discussion. SEM Analysis. The scanning electron microscopy (SEM) analysis of the samples coated with WC12Co powders provides detailed information about the microstructure of the layer obtained by thermal plasma spraying. This analysis is essential for evaluating the quality, material distribution and mechanical behaviour of the layer. From the SEM analysis, WC12Co particles in irregular structures are observed, dispersed in the cobalt matrix (Figure 3).

From particle analysis by scanning electron microscopy, a detailed characterization of particle size and morphology can be obtained. SEM allows for a precise assessment of individual particles. SEM analysis

Table 1. Particle size analysis of WC12 powders used for spraying
Таблиця 1. Аналіз розміру частинок порошків WC12, які використовуються для напilenня

| Value | r, μm | d, μm | A, μm ² |
|------------|-------|-------|--------------------|
| Min. value | 1.76 | 3.53 | 9.78 |
| Max. value | 14.68 | 29.37 | 677.47 |
| Mean value | 5.94 | 11.87 | 148.23 |
| Std. dev. | 3.46 | 6.92s | 173.55 |

where: r – radius of the particles, d – diameter of the particles, A – area of WC12Co particles.

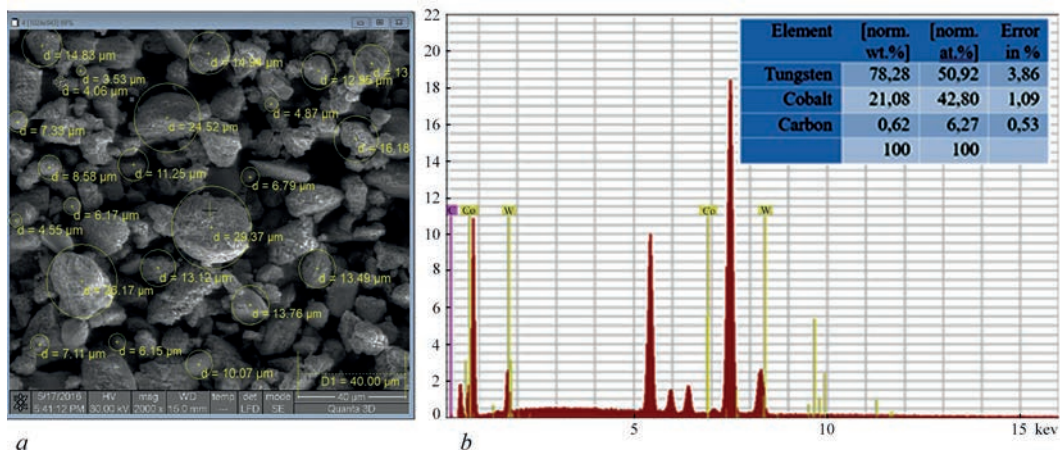


Figure 3. SEM images: a – determination of the size of WC12Co powders used for spraying, where: d – is the particle diameter; b – their EDX analysis

Рис. 3. SEM зображення: a – визначення розміру порошків WC12Co, які використовуються для напilenня, де: d – діаметр частинок; b – їхній EDX аналіз

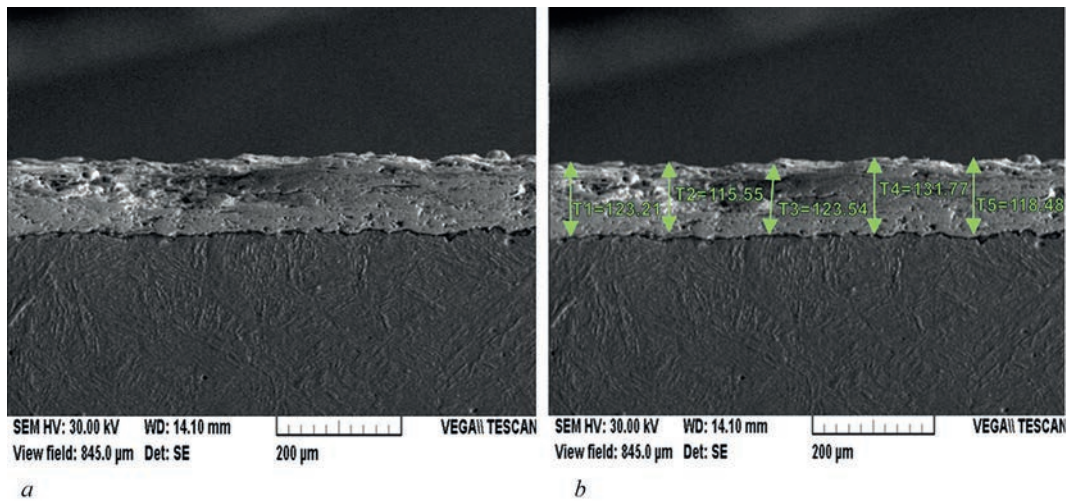


Figure 4. SEM image of the layer sprayed with WC12Co; *a* – SEM analysis, *b* – layer thickness analysis
 Рис. 4. SEM зображення шару, напиленого WC12Co; *a* – SEM аналіз, *b* – аналіз товщини шару

ysis allows for the observation of morphological details of WC-Co particles, which can have irregular, sharp or rounded shapes, depending on the manufacturing process.

Typically, WC12Co particles are regular, which favours a good mechanical bond in the coating layer. Dimensional measurements can be made directly on SEM images at a well-defined scale, ensuring precision in determining the particle size distribution (Figure 1). The determined size of the particles used is presented in table 1. It varies between 3 and 29 microns in diameter with their average diameters being approximately 5 μm and the area of 148 μm.

Tungsten cobalt carbide is known for its hardness and ability to resist abrasion, making it a material of choice in industries where wear protection and mechanical strength are essential.

The resistance of the coatings to hydro-abrasive wear and corrosion makes them ideal for applications such as hydraulic turbine blade coatings, dirty water pump coatings and in mining industries such as salt mining, where hydro-abrasive wear and corrosion are common problems.

For the analysis of the thickness of a coating sprayed with WC12Co, several measurement methods can be used. Among all the existing methods, thickness determination using electron microscopy was chosen because it offers high resolution and can measure very small thicknesses. Also, from the SEM image obtained, an analysis of the layer-substrate interface can be performed. Thickness measurements on SEM are of very high precision because it has the ability to measure thin layers at the nanometric level.

Determining the thickness of a coating of WC12Co sprayed using scanning electron microscopy involves several steps and techniques, which allow obtaining precise and detailed measurements of the layer thick-

ness. The sample made by thermal plasma jet spraying was sectioned perpendicular to the layer surface, to obtain a cross-section through the WC12Co layer and substrate. After cutting, it was embedded in an epoxy resin to protect the edge of the sample and facilitate subsequent handling in the grinding and polishing process. The samples were subjected to successive grinding processes, to obtain a flat and smooth surface at the interface between the layer and the substrate. In order to better highlight the layer and the substrate but also the interface between them, the samples were chemically etched prior to SEM analysis (Table 2).

The thickness of the layer can be measured directly on the SEM image, by calculating the distance between the layer-substrate interface and the upper edge of the layer. SEM images include a precise scale, allowing the thickness to be measured with very good accuracy. Also, for even greater precision of the thickness value of the sprayed star, measurements are made at several points along the layer section, the average of these measurements providing a precise estimate of the average layer thickness.

EDX analysis. EDX analysis is a technique attached to a scanning electron microscope and works by analysing the X-rays emitted by samples when they are bombarded with electrons. Each element emits characteristic X-rays, and the analysis of these

Table 2. Dimensional analysis of the sprayed coating
Таблиця 2. Аналіз розмірів напиленого покриття

| Object name | Thickness [μm] | Value | Thickness [μm] |
|-------------|----------------|------------|----------------|
| T1 | 123.21 | | |
| T2 | 115.55 | Min. value | 115.55 |
| T3 | 123.54 | Max. value | 131.77 |
| T4 | 131.77 | Mean value | 125.15 |
| T5 | 131.7 | Std. dev. | 6.81 |

where: T1–T7 – represents the names of the areas where the thickness determination took place on the SEM image in Figure 4.

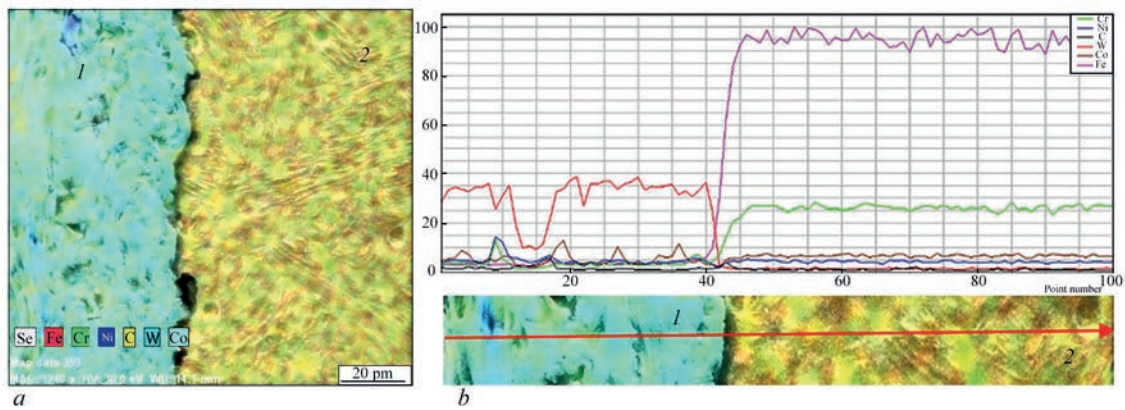


Figure 5. SEM images with EDX analysis of the sprayed layer (1) and the substrate (2); a – EDX mapping; b – in-line EDX analysis
Рис. 5. SEM зображення з аналізом EDX напиленого шару (1) і підкладки (2); a – відображення EDX; b – поточний аналіз EDX

radiations allows the identification and quantification of the chemical elements present in the sample.

From the SEM analysis performed in the section it can be seen that the interface between the layer and the substrate is very well determined, very uniform and without defects which indicates that the adhesion is very good. From the EDX compositional analysis presented in Figure 5 it can be observed a homogeneous distribution of the WC and Co layer.

Also, at higher magnifications areas with reduced porosity are observed. This is due to some particles that are partially melted. This is a characteristic of coatings made by thermal spraying, and the presence of pores can influence the mechanical properties of the layer, especially the resistance to wear and corrosion.

Conclusions

Hydropower plays a key role in the transition to renewable sources, but hydro-abrasive wear of turbines caused by solid particles in water is a major challenge. Reducing this type of wear through advanced vortex technologies and plant modernization is crucial to maintaining the efficiency and sustainability of hydroelectric systems.

Chemical analysis of the base material from a Francis turbine blade revealed that the stainless steel used, of the GX3CrNi13-4 grade, has a high chromium and nickel content, which gives it excellent corrosion resistance and good ductility. These properties are essential for hydraulic blades exposed to aggressive environments such as salt water.

By using SEM, precise measurements of the thickness of the WC12Co layer can be obtained, along with detailed information on the structure and uniformity of the spraying. This process is essential for validating the quality of the protective layer and the spraying parameters used.

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VIII Міжнародна конференція з питань цілісності конструкції та довговічності 2025 16 - 19 вересня 2025 року



ICSID 2025

Дубровник, Хорватія, 16-19 вересня 2025 р.

Метою конференції ICSID 2025 є об'єднання вчених та інженерів з усього світу для обговорення того, як характеризувати, аналізувати, прогнозувати та оцінювати втому та руйнування конструкційних матеріалів і компонентів. ICSID 2025 має на меті стати форумом для обговорення

поточних і майбутніх тенденцій в експериментальній, теоретичній і прикладній механіці руйнування, втомі, оцінці

цілісності конструкції, аналізі відмов та інших важливих тем у цій галузі. Конференція ICSID 2025 сприятиме співпраці між науковцями та експертами з університетів, промисловості та уряду, які займаються проблемами втоми та руйнування матеріалів і конструкцій. Для аспірантів, дослідників та інженерів з промисловості перед конференцією буде організовано дводенну школу з моделювання та аналізу втоми та руйнування разом із обговоренням за круглим столом на тему «Як поєднати науку та промисловість».



Тематика конференції:

- Передові методи тестування та оцінювання
- Аналітичні моделі
- Застосування до компонентів і конструкцій
- Штучний інтелект в аналізі структурної цілісності
- Корозія, деградація та розтріскування, викликані навколишнім середовищем, корозійна втома
- Циклічна деформація та зародження тріщин
- Механіка та моделі пошкодження
- Бази даних, експертні системи та програмне забезпечення
- Довговічність і продовження терміну служби конструкцій і компонентів
- Розслідування та аналіз несправностей
- Руйнування наноматеріалів і наноструктур
- Втома і руйнування полімерів, еластомерів, композитів і біоматеріалів
- Втома та руйнування зварних виробів, зварних компонентів, з'єднань і клеїв
- Моделювання втоми та руйнування та випробування на всіх масштабах довжини
- Прогнозування траєкторії втомної тріщини
- Методи скінчених елементів та їх застосування
- Руйнування та пошкодження цементних матеріалів
- Критерії руйнування та відмови
- Втома і знос
- Низька, середня та висока циклова втома
- Методи макромасштабного прогнозу втоми
- Обчислювальне моделювання мікроструктури в масштабі
- Змішана та багатоосьова втома та руйнування
- Моделі, критерії та методи в механіці руйнування
- Багатомасштабне моделювання матеріалів
- Неруйнівна оцінка (NDE)
- Імовірнісна механіка руйнування
- Надійність і цілісність інженерних споруд
- Ефекти залишкового стресу
- Оцінка цілісності конструкції
- Обробка поверхні та підвищення стійкості до пошкоджень
- 3D-друковані матеріали та конструкції

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