UNIVERSITATEA DIN PETROŞANI

ŞCOALA DOCTORALĂ

SUMMARY OF THE DOCTORAL THESIS

RESEARCH ON NON-DESTRUCTIVE TESTING USED FOR DIAGNOSING DEFECTS IN LIGNITE MINING EQUIPMENT

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Metal corrosion, Non-invasive investigation methods, Bucket wheel machinery, Non-destructive testing (NDT), Pitting corrosion

3. INTRODUCTION

The doctoral thesis titled "*RESEARCH ON NON-DESTRUCTIVE TESTING USED FOR DIAGNOSING DEFECTS IN LIGNITE MINING EQUIPMENT*" addresses an important topic for the mining industry in the context of lignite exploitation in the coal basins of Oltenia. The efficient and safe use of mining equipment is essential for optimizing mining operations and reducing the risks associated with their operation.

In the coal basins of Oltenia, lignite extraction is carried out using continuous action excavation systems that include bucket wheel excavators for overburden removal, high-capacity belt conveyors, stacker machines for tailings deposition, as well as equipment for coal handling. These complex systems require constant monitoring and effective diagnostic methods to ensure their performance and reliability.

This thesis aims to investigate the non-destructive testing methods applied in diagnosing the operation of lignite mining equipment. Non-destructive testing (NDT) encompasses a set of techniques that allow for the assessment of the technical condition of structures and components without causing damage or malfunctions. By using these methods, defects and degradations that occur during the operation of the equipment can be identified and analyzed, contributing to the extension of equipment lifespan and the prevention of accidents.

The research focuses on the analysis of equipment used in surface mining in the Oltenia basin. Particular emphasis is placed on the analysis of bucket wheel excavators, which are essential in the process of overburden removal and lignite extraction. The technical characteristics of these machines, the modernization solutions applied, and their impact on operational efficiency and safety were evaluated in detail.

Additionally, the thesis presents the results of research conducted on various non-destructive testing techniques such as ultrasonic testing, radiography, thermography, and other advanced methods, as well as how these can be integrated into preventive and corrective maintenance programs for the equipment. In this context, the study aimed to contribute significantly to the improvement of diagnostic and maintenance practices in the mining industry.

The final goal was to optimize the exploitation processes and reduce operational costs. The research results are significant for the mining industry in Romania and for other regions where similar technologies are used for mineral resource extraction. By efficiently implementing non-destructive testing techniques, sustainable and responsible exploitation of natural resources can be ensured, thereby contributing to sustainable economic development and environmental protection.

Structurally, the doctoral thesis comprises 5 content chapters, an introduction, conclusions and original contributions, as well as a bibliography of the cited works.

In **Chapter 1**, titled **CONTINUOUS ACTION LIGNITE MINING SYSTEMS**, these types of exploitation systems used in the coal basins of Oltenia are described. Emphasis is placed on the use of bucket wheel excavators, belt conveyors, and stacker machines for managing tailings and lignite. In Oltenia, the equipment used has an operational lifespan of over 20 years and has been modernized to improve efficiency and operational safety. The chapter details the characteristics and operation of the main types of excavators: ERc 1400-30/7, SRs 2000-30/7, and SRs 1300-26/3.5, highlighting their complex structure and the innovative component brought by modernizations. Additionally, the equipment for removing and depositing coal is presented, emphasizing the necessity of using non-destructive testing methods for diagnosing and maintaining this equipment.

Chapter 2, titled **THEORETICAL CONCEPTS REGARDING CRYSTALLINE STRUCTURE AND METAL CORROSION**, presents theoretical concepts regarding crystalline structure and metal corrosion, focusing on the materials used for the load-bearing structures of mining equipment. The steels used and their associated standards are also presented, highlighting the importance of chemical composition and mechanical characteristics. The physical degradation process of materials, including elastic, plastic deformation, and fracture, has been analyzed, and the types of crystal structures and their associated defects have been described. The chapter also addresses the phenomenon of metal corrosion, classifying the types of corrosion based on the distribution of the attack and the environment in which it occurs. Methods of corrosion protection, including the use of inhibitors and electrochemical protection, are detailed, emphasizing the importance of preventing deterioration to extend the lifespan of mining equipment.

In **Chapter 3** of the thesis, titled **NON-DESTRUCTIVE TESTING METHODS FOR LOAD-BEARING STRUCTURES IN BUCKET WHEEL MACHINERY**, non-destructive testing methods applied to this type of structures used in the mining industry are analyzed. Diagnostic techniques such as defectoscopy, including liquid penetrant testing, magnetic particle testing, radiography, and ultrasound, are also presented. This chapter details the types of defects that can occur in equipment, including design, manufacturing, and assembly defects. The importance of identifying and evaluating these defects to prevent damage and extend equipment life is emphasized. The role of visual inspections and advanced control methods in ensuring safety and operational efficiency is highlighted.

In **Chapter 4**, titled **NON-DESTRUCTIVE CONTROL OF CORROSION AND ITS INFLUENCE ON THE STRUCTURE OF ROTOR MACHINERY**, the non-destructive control of corrosion and its influence on the structures of rotor machinery used in mining operations is examined. Various types of corrosion, such as general corrosion, pitting corrosion, crevice corrosion, and fretting corrosion, are analyzed, detailing the causes and effects of each on structural integrity. Non-destructive evaluation methods such as ultrasonography are analyzed for detecting and quantifying corrosion-induced damages. The chapter includes a case study on the analysis of the clamping plates of the ERc 1400-30/7 excavator supports, highlighting the techniques used for measuring thickness and assessing the state of material degradation.

In **Chapter 5**, titled **MODELING PITTING CORROSION**, the modeling of pitting corrosion is presented. This localized corrosion process affects metal surfaces by forming cavities. The mechanisms of cavity growth have been analyzed through kinetic simulations, which included mass transfer and geometric deformation of the model subjected to simulation. The simulation was performed using Comsol Multiphysics and involved the analysis of chemical reactions such as oxygen reduction and iron oxidation, leading to the formation of iron hydroxide in the simulated cavity. The modeling and simulation of corrosion over a period of 40 days utilized variables such as salinity, pH, and electrolyte temperature. The obtained results demonstrate the increase in the density of the iron dissolution current and the variation of pH over time, thus highlighting their importance in accelerating the corrosion process in cavities.

4. CONCLUSIONS AND FINAL RECCOMENDATIONS

The doctoral thesis addresses an important subject for the lignite exploitation activity in the coal basins of Oltenia. The research aimed at reducing the risks associated with the operation of continuous action machinery and optimizing the mining operations in which these machines are involved.

The category of continuous action machinery includes bucket wheel excavators for overburden removal, high-capacity belt conveyors, stacker machines for tailings disposal, and equipment used for coal handling. The complexity of the aforementioned machinery necessitates continuous monitoring through diagnostic methods to ensure their performance and reliability. Given that the equipment used for lignite extraction in the Oltenia coal basin has been operational for over 20 years, having been built between 1975-1990, the need for diagnosis and monitoring of potential defects is even more critical.

To determine the necessary workload for diagnosing and monitoring defects that may arise from the operation of machinery with load-bearing metal structures, an inventory of these machines was conducted, presenting their structural and functional characteristics.

To better understand the material degradation phenomena in surface mining equipment, elastic (reversible) deformations, plastic (irreversible) deformations, and the phenomenon of fracture were analyzed. Since the load-bearing structures of the equipment in surface mining are constructed from metals, the analysis focused on the face-centered cubic, body-centered cubic, and hexagonal close-packed crystalline structures. The mechanical properties of metals are modified through alloying, which involves altering the ideal crystalline structure of the metal, leading to dynamic and static imperfections over time. Static imperfections can be geometrically point-like or linear, including dislocations. As dislocations can contribute to increasing a material's hardness and fracture resistance - known as dislocation strengthening - edge and positive dislocations were presented. The quantitative definition of crystalline lattice deformation due to dislocations is determined using the Burgers vector. The analysis concluded that the Burgers vector for an edge dislocation is perpendicular to the dislocation line, while for a screw dislocation, it is parallel to the dislocation line.

In mining equipment, the metal structures are subjected to deterioration through corrosion caused by chemical or electrochemical reactions due to the aggressive environment in which they operate. Under these conditions, the contact between atmospheric oxygen and the excavated material leads to chemical reactions with the hydrogen and carbon present in lignite, resulting in carbon dioxide, sulfur, and water vapor, which affect the exposed metal surfaces of the equipment, potentially leading to their eventual decommissioning.

The study of the corrosion phenomenon allowed for the classification of corrosion based on attack distribution and the environment in which the attack occurs.

The main methods of protecting metals against corrosion were presented according to their mode of action. These include: the method of reducing environmental aggressiveness, the method of increasing the corrosion resistance of metals and alloys, electrochemical protection methods, and protection based on surface coating of the equipment.

Non-destructive testing techniques are the most commonly used in analyzing defects in the load-bearing structures of surface mining equipment. These techniques are characterized by the fact that the material being tested is not destroyed and can be reused. The set of non-destructive testing techniques is also referred to as defectoscopy.

When a defect arises, identifying its origin is crucial for eliminating the underlying cause. Defects can thus be classified into design defects, manufacturing defects, installation defects, and defects due to improper operation of the equipment.

Non-destructive testing methods depend on the location of the imperfections. For surface imperfections, superficial up to a few millimeters deep (on the exterior), the non-destructive methods used are liquid penetrant testing and magnetic particle testing. For imperfections fully embedded within the section (on the interior), radiographic and ultrasonic non-destructive testing methods are employed.

The equipment used in surface mining operations is exposed to the effects of weather factors such as rain, wind, or snow, and to chemical factors such as salts, sulfides, or other compounds emitted by the excavated material. Both weather and chemical factors lead to the gradual structural degradation of load-bearing elements, mechanisms, and cables through corrosion.

Due to certain types of loads that can cause deformations or accidental impacts on the load-bearing structures, the stability of the load-bearing assembly may be compromised, potentially generating discontinuities or cracks. Monitoring the condition of load-bearing elements and performing periodic technical inspections are essential to prevent these issues.

Thus, visual inspection is crucial for checking safety mechanisms and load-bearing elements that need to be periodically inspected, such as the visual inspection of a load-bearing beam from the bucket-wheel arm. The purpose of this non-destructive testing is to detect visible defects on the surface of the beam. If a structural issue is identified, deformation measurements of the beam are carried out. Therefore, using measuring tools and devices provides additional information about the characteristics and quality of the tested components.

Another simple and frequently used non-destructive testing method for detecting surface defects in various materials is liquid penetrant inspection. The disadvantage of this testing method is that it cannot detect defects that are not open to the surface, such as internal defects or those covered by paint or other substances. However, due to its low cost and minimal effort involved, this technique is effective and widely used across various fields. The liquid penetrant defect detection method can produce three types of indications: conclusive indications, inconclusive indications, and false indications. The thesis presents a case study in which liquid penetrant inspection was performed on the spherical support subassemblies, the central column mounting plate, and the ring beam of the ERc1400-30/7 bucket-wheel excavator.

For weld control and the measurement of the thickness of structural elements, technologies based on ultrasound are used. In this context, the physical principle of ultrasonic analysis, the method of generating ultrasound, types of transducers (quartz, barium titanate, and lead zirconate), and the functioning of ultrasonic transducers were presented.

I participated in performing periodic maintenance and technical analysis for the ERc 1400-30/7 excavator. Non-destructive methods for diagnosing the load-bearing structure of the equipment were used. Initially, the overall condition of the structural assembly was checked through visual inspection.

A second type of control used was liquid penetrant inspection. To verify the thickness and integrity of the welds, ultrasonic testing was conducted. The equipment used for ultrasonic testing was presented in the work.

It can be concluded that non-destructive investigation methods for the load-bearing structures of bucket-wheel excavators enable timely detection of defects, thus avoiding equipment shutdowns followed by costly delays caused by maintenance and repair activities.

Additionally, it can be concluded that each non-destructive investigation method has its own advantages and limitations. The choice of the most effective method depends on the nature and location of the defect. In these conditions, evaluating working conditions, using appropriate technology, and performing continuous monitoring are crucial to ensure the efficient and safe operation of bucket-wheel excavators in lignite quarries.

In the equipment used for lignite extraction in surface mining operations, corrosion is a common issue due to the fact that lignite, in contact with air oxygen, leads to the formation of carbon dioxide/sulfur and water vapor. It is also observed that corrosion damage tends to have a similar distribution across all equipment used in surface mining operations. Therefore, it can be concluded that the methods for preventing corrosion damage to this equipment have a general applicability.

The rejection of evaluating corrosion-induced degradation through destructive methods, which involve taking samples from the load-bearing structure of heavy mobile equipment, leads to the conclusion that non-destructive analysis methods are the only viable approach for assessing this phenomenon in the load-bearing structures of equipment used in surface mining operations.

It has been shown that the forms of corrosion attack, depending on the degree of detectability, are divided into three groups: corrosion detectable by visual inspection, corrosion detectable with specialized investigation equipment, and corrosion detectable through microscopic examination. Examples for surface mining equipment include general corrosion, pitting corrosion, crack corrosion, and fretting corrosion.

Using the non-destructive ultrasonic method to evaluate corrosion, a case study was conducted on the shims of spherical bearings of the base chassis for four ERc1400-30/7 excavators operating within the Complexul Energetic Oltenia S.A – E.M.C. Roșia-Rovinari. The shims, designed to be 30 mm thick and made from OL52-3k steel, were examined. The excavated material deposited on the shims represents the corrosive environment. Visual inspection revealed that under the corrosive environment, exfoliation corrosion and pitting corrosion, which developed under exfoliation corrosion, were present. It was also observed that the tensioned fastening bolts exhibited stress corrosion. Ultrasonic thickness analysis of the shims highlighted that the corrosion phenomenon leads to a reduction in their thickness in all four analyzed excavators. It can also be concluded that the level of corrosion does not reach a maximum value for the excavator with the highest operating hours.

Computer modeling and simulation methods were used to study pitting corrosion. Local cavities characterizing this type of corrosion are initiated due to surface defects, such as composition or shape inhomogeneities, or as a result of a mechanical action that creates a small scratch. The growth of the cavity size is influenced by the type of metal, salinity, pH, and temperature of the aqueous electrolyte that penetrates the cavity. Understanding the pitting corrosion process is essential for the proper selection of materials used in environments prone to this type of corrosion.

The fundamental mechanisms of cavity expansion were investigated through kinetic simulation of the electrode, mass transfer, and geometric deformation of the resulting cavity. For pitting corrosion, it was hypothesized that the oxygen reduction reaction occurs primarily on the metal surface outside the cavity.

The simulation was performed using the Comsol Multiphysics application. It involved analyzing chemical reactions such as oxygen reduction and iron oxidation, which lead to the formation of iron hydroxide in the simulated cavity. To simulate pitting corrosion over a period of 40 days, various variables such as salinity, pH, and electrolyte temperature were used.

The results from the simulation lead to the conclusion that the iron dissolution current density after 40 days is higher inside the cavity than outside it. Additionally, a pronounced convex-shaped cavity develops beneath the affected metal surface.

Another conclusion drawn from the analysis of the results is that the lowest initial pH is located inside the cavity at its lower part, with an approximate value of 9.53. At the end of the simulation process, the lowest pH is approximately 8.61, also corresponding to the lower part of the cavity. It can be concluded that the decrease in pH explains the increased rate of iron electrode dissolution over time (the rate of cavity size growth).