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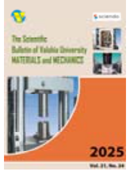

HARD CHROMIUM PLATING: TECHNOLOGICAL CHALLENGES, ENGINEERING APPROACHES, AUTOMATION AND INNOVATIVE SOLUTIONS FOR OPTIMIZED INDUSTRIAL PROCESSES

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Abstract: *This paper analyzes the evolution of chromium plating installations, from empirical and traditional methods to modern continuous systems, emphasizing the technological, economic, and ecological differences. Hard chromium plating, an essential electrochemical process for enhancing wear and corrosion resistance, has faced major limitations in its conventional form: high energy consumption, non-uniform deposits, and significant risks to the environment and workers' health. Modernization through the implementation of continuous plating systems, based on horizontal bar movement and strict control of electrochemical parameters, has brought substantial advantages: reduced electrolyte volumes, improved deposit quality, optimized energy consumption, and minimized environmental impact. Romania, as a European leader in chromed bar production, directly benefits from these advancements, consolidating its industrial competitiveness and strategic position on the international market.*

Keywords: *Chrom Plating, Technology, Environment, Sustainability, Optimization*

1. INTRODUCTION

In stainless steels, the incorporation of chromium into the alloy chemical composition directly influences corrosion resistance, hardness, and material durability. Chromium-alloyed steel products are widely used in the manufacture of tools, springs, bearings, and components subject to mechanical wear. Careful control of chromium content is essential: insufficient levels reduce corrosion protection, whereas excessive chromium generates the formation of brittle intermetallic phases that affect the durability of the material. In stainless steels, chromium is used in concentrations up to 30%, often combined with nickel, contributing both to the stabilization of the cubic crystal structure of iron and to the formation of a passive protective film on the surface of the material. This film reduces the oxidation reactions and protects the steel from corrosive environments.

In addition to being integrated into the alloy, chromium can be applied via electrodeposition, which substantially improves the surface properties of steel bars. The electrolytic reactions involve the ionization of chromic acid (H_2CrO_4) and the formation of chromate (CrO_4^{2-}) and dichromate ($Cr_2O_7^{2-}$) oxyanions, which are the primary chromium ion carriers during the deposition process. The process parameters—current density, pH, temperature, and electrolyte composition—influence the quality of and thickness of the coating. Thin coatings tend to be brittle, while thicker coatings develop a network of microcracks that functionally retain lubricants, thereby reducing friction and increasing the service life of the components [1-5].

Functional chromium plating, or hard chrome plating, is an electrochemical chromium deposition process on metal surfaces, resulting in coatings with high wear resistance, elevated hardness, and increased corrosion protection. This technology is particularly important for long metallic bars, where the coating uniformity is a critical condition for final performance of the product.

The classical, discontinuous method involves vertical handling of the bars via the upper section of the tank, employing lifting and handling equipment, which constraints efficiency and increases operational costs. To overcome these constraints, the industry has developed continuous hard chromium plating plants, where workpieces move horizontally and consistently through low-volume electrolyte baths, in a fully automated process from loading to unloading.

At the European level, the development of continuous plating plants is concentrated around a small number of established manufacturers (Aslan Tech S.r.l., Loeser GmbH, and Ilmar S.r.l.). However, what is of particular interest is the fact that Romania has emerged as the largest European producer of chromium-plated bars, positioning itself as a true "industrial hub" in this field. Companies such as ASO Cromsteel SA, Nimet SRL, Tristar Steel SRL in Târgoviște, and Proinvest SRL in Pașcani represent key players in the global supply and production chain of chrome-plated rods and the optimization of chrome plating processes has a direct impact on their competitiveness in the market This reality means that research and innovation in the field are not just an academic exercise, but a strategic priority for Romanian industry and for the consolidation of its role at European and global level..

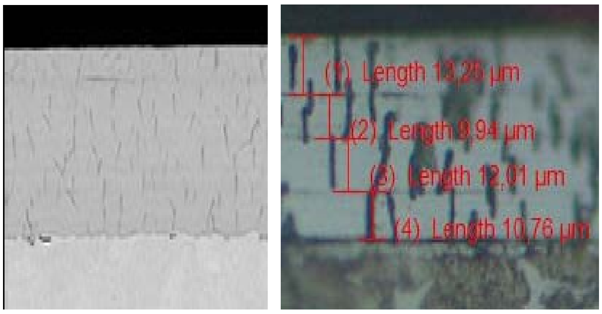
2. CONSIDERATIONS REGARDING THE DEPOSITION OF CHROMIUM LAYERS IN THE PLATING PROCESS

From a scientific point of view, chromium plating occupies a distinctive role among electroplating coatings due to its combination of unique properties of the deposited coating: low friction coefficient, high hardness, and high corrosion and wear resistance. Although its industrial application came relatively late, the process has much older origins, having been discovered by Bunsen in 1854 and perfected by Geuther in 1856. The seven-decade interval between discovery and commercial application stands as a eloquent example of how scientific principles can remain dormant until an appropriate technological and economic framework is established for their exploitation [6].

Current classifications of chromium plating types depend on the coating thickness. Thus, according to Nenad Mandich, deposits ranging from 0.5–8 µm fall within the ornamental category, corresponding to decorative chrome plating, while layers up to 1000 µm define hard chromium plating. Opinions, however, diverge regarding the composition of the electrolyte: Neeraj Jain *et al editors* argue that both decorative and functional chromium plating rely on hexavalent chromium, whereas Cristiano Poltronieri clearly distinguishes between the two types, attributing hard chromium plating to Cr^{6+} solutions and decorative chromium plating to Cr^{3+} solutions. Current research trends are converging towards the replacement of hexavalent compounds, recognized for their toxicity — with Cr^{3+}-based alternatives, less hazardous for the environment and operators' health [3,4,7].

In this context, Andrea Franceschetti highlights the central role of the electrolyte bath, where electrochemical deposition reactions occur. Its parameters, correlated with the desired type of coating, determine the deposition quality and performance. Even though the use of hexavalent chromium poses serious environmental concerns, deposits obtained from such solutions display a combination of properties that no alternative technology has yet equaled, which explains why hard chromium plating remains widely used. Moreover, its applicability across a broad range of substrates consolidates its role as a reference technology in multiple industrial fields [8,9].

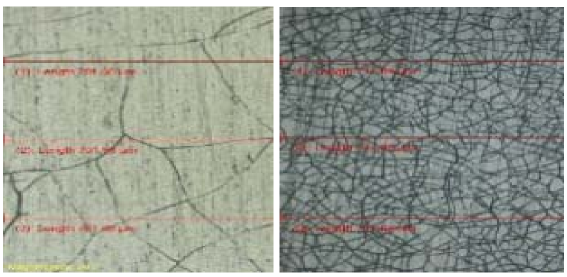
The thickness of the chromium layer may be uniform and compact or arranged in several layers (Fig. 1 a/b). This is determined by parameters such as exposure time and applied current density, while the quality of the layer depends on electrolyte composition and current intensity. In hard chromium plating, the preliminary surface preparation of the workpiece plays a decisive role in the deposit morphology. Irregularities arising from grinding and polishing can generate residual stresses, which may lead to macro-cracks following the electrodeposition process [4].



a b

Figure 1. Chromium deposit: single layer (a); multi-layer (b) [1,10]

The chromium deposition occurs at extremely negative cathodic potentials and is accompanied by significant hydrogen release. This phenomenon results in low current efficiency and promotes the occurrence of porosity and hairline cracks within the deposited layer. Very thin coatings, below 0.5 µm, exhibit low resistance, but as the thickness increases, a characteristic network of cracks develops in the layer structure (Fig. 2). Functionally, these micro-cracks act as lubricant retaining networks, thus contributing to the reduction of friction and increasing the service life of moving components [1].



a b

Figure 2. Micro-cracks in electrolytic chromium deposition (200x): unpolished specimen (a); polished specimen (b) [1]

3. EVOLUTION OF CHROMIUM PLATING TECHNOLOGIES AND THEIR SPECIFIC CHARACTERISTICS

3.1. Historical Overview

The earliest attempts to obtain chromium deposits can be considered empirical, based on experimental observations rather than on a scientific understanding of the electrochemical phenomena involved. At this stage, reproducibility of results was difficult, yields were low, and control over layer thickness and quality was limited. Nevertheless, these efforts paved the way for defining the fundamental principles of chromium electrochemical deposition.

Subsequently, with the development of electroplating plants and the refinement of electrolyte solutions, the transition was made to what we now call traditional chromium plating. This was carried out in large tanks into which parts are placed vertically. Although this method allows the production of chromium layers with significant mechanical and anti-corrosive properties, it raises major logistical challenges: difficult handling of parts, high electrolyte consumption, and low energy yields.

Technological developments in the last decades have led to the implementation of modern chromium plating, characterized by a rigorous control of process parameters and automation of production flows. Particularly for large steel bars, continuous chromium plating plants have replaced traditional methods. In this system, the parts move horizontally through greatly reduced electrolyte baths, ensuring uniform deposits, optimized material and energy consumption, and integration into fully automated technological lines. This modern approach not only eliminates the constraints imposed by vertical handling but also contributes to increased productivity and quality of protective coatings.

Chromium plating — in both its decorative and forms — falls within the scope of electroforming, processes that use electrolysis to deposit a protective metallic layer on a supporting substrate. The discovery of chromium by Nicolas Vauquelin (1797) and the invention of the voltaic pile (1800) paved the way for the development of electrochemical processes. The first practical demonstrations of electroplating were performed by Luigi Brugnatelli (1805), who demonstrated the deposition of gold on electrodes, and later contributions by Antoine Becquerel integrated batteries into the sequence of electroplating processes, facilitating productivity and control of experimental processes (Fig. 3). Early limitations concerned unstable current sources, low yields and the lack of standardized electrolyte solutions, obstacles that delayed the transition to large-scale commercial applications [11-13].

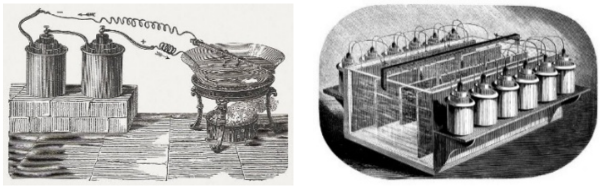


Figure 3. Early electroplating configurations [14]

The first industrial breakthrough of the process, however, came with the patent registered by George Elkington in 1860, together with his cousin Henri and with John Wright. They are considered to be the pioneers of commercial electroplating, a process that would expand in the early 20th century with the introduction of the dynamo as a source of direct current. The new equipment considerably extended the scope of applications, making the deposition of metals such as zinc, copper and nickel possible, in parallel with the refinement of electroplating solutions and plants [11,13].

Research into chromium plating as a practical process gained momentum in the first half of the 20th century. The first significant studies and experimental applications appeared between 1920–1927, through the contributions of Robert Elliott, Robert Duncan, and later through the patents and studies of Robert Fetherolf and Jesse Sherwood, who demonstrated the possibility of obtaining hard and adherent chromium deposits on various metallic substrates. The main technical challenges of the time included controlling coating uniformity, low current yield (influenced by hydrogen evolution at very negative cathodic potentials) and the occurrence of micro-cracks and porosity in the deposit. Later progress — such as pulse plating, electrolyte optimization, and equipment automation in the 1960s — helped overcome many of these constraints, increasing the process quality, consistency, and productivity [15–17].

3.2. General Aspects of Coating Technologies

In this context, coating methods are essential for protecting materials and optimizing functional performance. The selection of appropriate technology must be correlated with application requirements, aiming both at preventing and delaying materials degradation processes. This implicitly leads to increased durability and reliability of components, which explains the transition from empirical electroplating to modern chromium plating technologies increasingly oriented towards quality control and process sustainability [18].

Chromium electrodeposition in conventional plants utilizes discontinuous lines with simple kinematics of the workpieces undergoing treatment. Steel rods are vertically suspended and introduced into an electrochemical tank, equipped with lateral anodes made of lead-tin-antimony alloys (97/5/3), immersed in a chromic acid-based electrolyte solution. The vertical configuration of the assembly imposes space constraints within the production hall, requiring high heights and auxiliary handling equipment (overhead cranes, fastening systems, and supporting structures) to ensure the operational flow.

The surface preparation steps include the human activities of chemical and mechanical degreasing, followed by fixing the bars in the cathodic holder and placing them in the chromium bath. The electrochemical pickling operation (anodic attack) is intended to remove the film of oxides resulting from the machining or the interphase dwell time. During this phase, Fe^{3+} impurities appear in the electrolyte due to the use of a single chromium plating bath, gradually reducing current yield. Surface cleaning is carried out by polarity reversal, where electrons are directed against the electrodeposition process, increasing the adhesion of the chromium layer. Washing of the bars is often performed above the chromium plating bath, which increases the risk of environmental pollution, representing a technological limitation of such plants [1].

As illustrated in Figure 4, conventional chromium plating plants provide an important advantage in terms of high flexibility for processing workpieces of varying sizes. The configuration of the bath allows quick transitions between very different diameters without requiring major structural changes.

Figure 4. Cathode configuration in traditional chromium plating plants [19,20]

The preparation and loading stages of the workpieces onto the cathodic holder are carried out in a specially designated area, where operators manually perform degreasing or use specially designed baths with dedicated solvents, that require additional space. Besides the significant floor space requirement, this type of plants also presents the major drawback of being highly dependent on the human factor during surface preparation (Fig. 5). Incomplete or improper cleaning can compromise the adhesion of the chromium coating, leading to defects such as penetrated pores, surface inclusions, or deposit unevenness, which considerably reduce the efficiency of the protective coating, affecting the anti-corrosion performance of the workpieces.

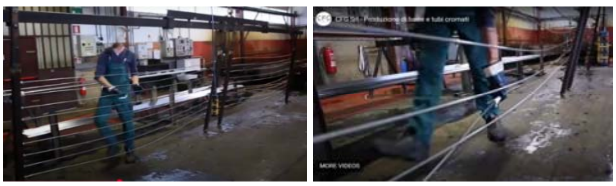


Figure 5. Surface preparation in traditional – hard chromium plating plants [21]

According to Figure 6, another significant disadvantage of traditional chromium plating plants is the material loss generated at the ends of rods subjected to the process. In areas of contact with the cathodic support, chromium deposits are often uneven, excessive or insufficient, leading to the removal of approximately 3% of the total length of each workpiece by cutting. This technological surplus not only results in the loss of the base material but also generates additional costs related to handling and performing the cutting operation, expenses that inevitably reflected in the final price of the product.

Figure 6. Technological losses [21]

The most significant disadvantage of traditional chromium plating plants is their negative impact on the environment and the operators' health. These systems use large volumes of electrolyte, which, under European legislation, severely limits their operation. Major risks are related to potential spills or accidents that can irreversibly contaminate soil and groundwater. The configuration of the baths, combined with the loading and unloading of bars from the top, often reduces the efficiency of the ventilation systems and fume hoods, promoting air pollution and exposing workers to toxic vapors. Prolonged contact with degreasing agents and the bath electrolyte is associated with serious occupational diseases, sometimes even fatal.

From an energy perspective, the yield of these plants is low: standard electrolyte baths achieve only 10–12% yield, while catalyzed baths reach approximately 20%. The process operates at temperatures above 65°C and current densities between 30–100 A/dm², producing layers with hardness values ranging from 650 to 1100 HV01. Increasing the current density proportionally reduces deposition time, but the layer uniformity remains deficient. Due to the placement of the anodes along the bath walls and the large distances between the supporting fixtures, the electric field is not concentric, resulting in uneven deposition: thicker at the ends and in the horizontal plane, as illustrated in Figure 7 [1,22].

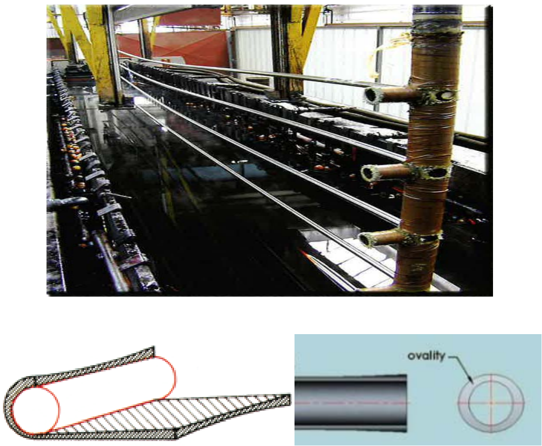


Figure 7. Traditional chromium plating bath and flowchart of the traditional chromium plating process [19,23]

The critical assessment of the studied traditional chromium plating plants highlights several structural and functional limitations, reflected not only in high energy consumption and low process efficiency but also in negative environmental effects and occupational health and safety risks. Manual handling of rods by operators, variability in chromium layer deposition, and material losses due to trimming of rod ends are factors that compromise technological efficiency and economic competitiveness. In this context, the need for modern chromium plating plants capable of eliminating human errors, optimizing productivity, and ensuring consistent quality of the finished products, while reducing environmental impact and occupational risks becomes evident. Modernization through automated solutions and advanced technologies thus emerges as an inevitable and strategic direction for the progress in the field.

A decisive milestone in eliminating disruptive factors in hard chromium plating was the introduction of Programmable Logic Controllers (PLC) assisted plants, which anticipated the transition to continuous chromium plating. These systems excluded direct operator intervention in the kinetics of the process in highly toxic areas, and their integration brought a clear sequencing of the technological steps: from chemical degreasing and intermediate rinsing to anodic attack, actual chromium plating, and final washing. Operators remained involved only in the loading and unloading of the bars, while transfers between baths were managed computer-controlled via overhead cranes coordinated by signals from transducers and sensors (Fig. 8). This innovation significantly reduced environmental and occupational health risks, but challenges related to energy consumption, costs, and productivity persisted.

From these limitations emerged the concept of continuous chromium plating plants, based on a new technological architecture, either with a single plating cell or multiple cells. Modernization focused not only on the logistics and kinematics of the process but also on the integration of electrochemical parameters into computer-controlled systems, optimizing the deposition of the chromium layer and ensuring greater uniformity. At the same time, electrolyte volumes have been significantly reduced, and bath structure has been redesigned with a new anode arrangement, allowing the continuous movement of the bar and successive formation of the protective metallic chromium layer.

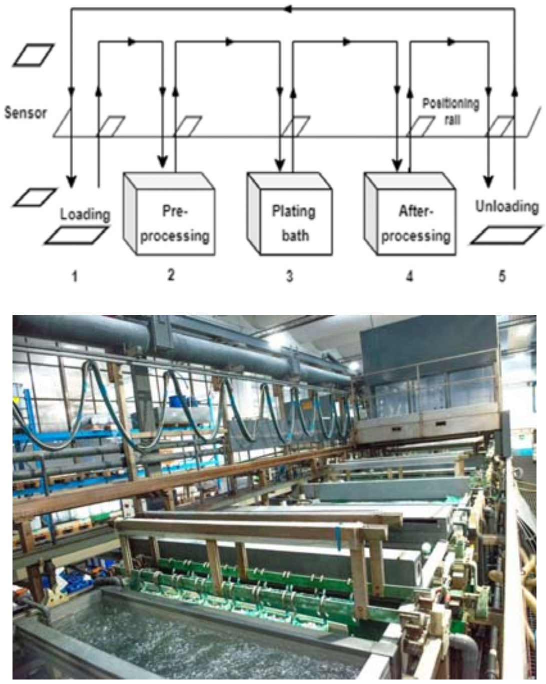


Figure 8. Chromium plating plants assisted by programmable controllers [8,24]

The natural evolution of the process of improving chromium plating plants has led to the development of multi-cell continuous chromium plating lines, designed to overcome the limitations of previous systems (Fig. 9). These plants introduced a new operational philosophy based on the fragmentation of the process into a sequence of independent cells, each dedicated to a specific technological stage. This modular structuring achieved significant advantages: increased uniformity of the deposited layer, the ability to fine-tuning the electrochemical parameters according to the processed section, and reduced dwell times. Moreover, the compact layout of the cells allowed for decreased electrolyte volumes and better workflow management, enhancing both productivity and operational safety.

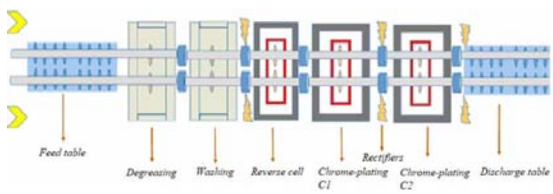


Figure 9. Kinematic diagram of the multi-cell chromium plating process [1]

The kinematics of continuous multi-cell chromium plating lines are based on the automatic and uninterrupted horizontal transport of the bards from the loading stage to the unloading. Along this route, the bars undergo a rigorously defined sequence of surface treatments: degreasing, intermediate rinsing, anodic attack, and chromium plating. This sequential arrangement allows the layered deposition of metallic chromium, resulting in a uniform coating tailored to the functional requirements of the final product.

The kinematic flow is supported by a set of transfer lines, also known as push-and-pull roller conveyors, which ensure the transport and positioning of the bars throughout the process. These operate using geared motor systems and rack-and-pinion mechanisms, designed to convert rotational motion into a controlled translational movement. This design ensures continuous and precise transport, reducing positioning errors, and contributing to the kinematic stability of the plant [1].

Figure 10. Continuous chromium plating plants with multiple cells [1]

If the multi-cell chromium plating plants were developed to meet high productivity requirements and to ensure stratified chromium deposition, more compact technological solutions based on a single chromium plating cell have also emerged in parallel. These plants retain the general philosophy of automation and strict parameter control but simplify the kinematic flow by integrating the main electrolytic deposition stages into a single-unit structure. Instead of a sequence of separate baths, the process is concentrated within a single working module, volumetrically optimized to reduce electrolyte consumption and material losses.

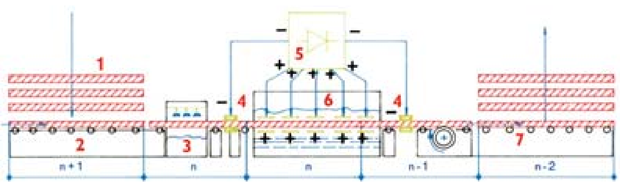


Figure 11. Kinematic diagram of the single-cell chromium plating process [23]

The kinematic chain, illustrated in Figure 11, closely resembles that of multi-cell continuous chromium plating plants, consisting of the automatic and continuous horizontal movement of the bars from loading to unloading. Along this route, they undergo surface treatments in a predetermined order—degreasing and chromium plating — resulting in the formation of a multi-layered metallic deposit, depending on the number of anode groups arranged longitudinally along the bar trajectory. Movement is ensured by push-and-pull roller tracks, supported by geared motor systems and rack-and-pinion mechanisms that convert rotational motion into translation.

Figure 12. Continuous chrome plating installations with a single chrome plating cell [25,26]

In conventional plants, the bars subjected to the chromium plating process are kept stationary, being fixed both mechanically and electrically to the cathodic support, which is directly connected to the collector bar. The kinematics of the process is simple, based on the controlled immersion of the assembly into the electrolyte bath, either in a horizontal or vertical position, for the time required to deposit the coating. The star-shaped anodes are arranged along the bath walls, providing the electric field necessary for the deposition process. By contrast, in modern continuous chromium plating plants, the bars move along the entire length of the technological line, and the electrical contacts move simultaneously over varying distances. The kinematics thus become sequential, as the surface of the bar is successively subjected to degreasing, electrochemical pickling and chromium plating.

Continuous hard chromium plating plants exhibit a range of technological, economic and environmental, advantages that clearly distinguish them from conventional systems. Firstly, the kinematics of the process are optimized by moving the bars horizontally, which eliminates the need for high production halls and reduces the complexity of fitting overhead cranes with guided lifting systems. Moreover, the replacement of operations during the chemical and mechanical degreasing stages has contributed to a safer and friendlier working environment, with direct benefits for occupational health and safety.

A second major advantage is the increase in the quality of deposition and the efficiency of the electrochemical process. This result is due to maintaining a clean electrolyte by separating the electrolytic pickling and chromium plating stages in separate baths, and the use of closed washing baths with high-pressure nozzles, which significantly reduce the pollutant impact. In addition, fully sealed suction and ventilation systems allow a recirculation of the chromium vapors and their reintegration into the electrolyte solution, which significantly reduces chromic anhydride consumption and mitigates environmental pollution, both within and outside the facility.

From an economic and safety standpoint, continuous chromium plating plants use reduced electrolyte volumes: approximately one-quarter of those in conventional baths. This feature eliminates the risk of major accidental spillages and simplifies the management of spent solutions more easily. The amount of resulting hazardous sludge generated is also considerably lower and the costs associated with its treatment and disposal are considerably reduced. Furthermore, the chemical control of the solution is more precise, ensuring stability and performance of the deposit.

Finally, continuous hard chromium plating plants eliminate the material losses generated at the unchromated heads of the bars due to the uniform coating over their entire length. The circular configuration of the anodes, through which the bars move equidistantly, ensures consistency and homogeneity of the deposited layer, the absence of geometric defects, and higher energy yield (Fig. 13). With all these improvements, continuous chromium plating establishes itself as a modern, efficient, and sustainable solution, fully in line with the current requirements of the industry.

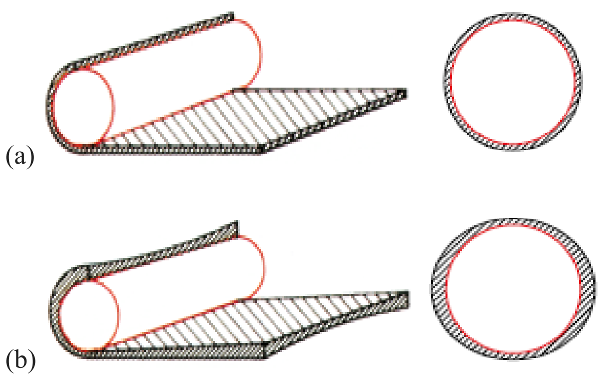


Figure 13. Chromium deposit achieved by continuous plating (a); conventional plating (b) [23]

The evolution of chromium plating plants, from traditional to modern continuous methods highlights the transformation of a polluting and limited technology into a high-performance, sustainable, and competitive process. Conventional plants, although flexible, have been characterized by high energy consumption, material losses, and negative impact on both the environment and operators' health. By contrast, continuous chromium plating plants optimize the kinematic workflow, reduce electrolyte volumes, ensure a strict control of electrochemical parameters, and achieve uniform deposition along the entire length of the bars. The benefits translate into higher efficiency, lower costs, and compliance with environmental regulations. Thus, continuous plating emerges as a cutting-edge technological solution, indispensable for the competitiveness of the Romanian industry and for consolidation of its position on the European and global markets.

4. CONCLUSION

The comparative analysis of traditional versus continuous chromium plating plants provides a comprehensive understanding of the advantages and limitations inherent to each technological solution. In traditional plants, the metal parts are mechanically and electrically fixed to the cathodic support and statically immersed in electrolyte baths, within a process that is simple in terms of kinematics, but with multiple implications on the productivity and quality of the deposited layer. This method stands out through its increased versatility: it can be applied to a wide variety of parts, including those with atypical dimensions or small batches. At the same time, however, conventional chromium plating involves major limitations related to material losses at the non-chromated ends, high electrolyte consumption, and infrastructure requirements such as high halls and lifting equipment necessary for vertical loading of parts. Moreover, direct operator contact with chemicals and limitations of the ventilation systems increase health and safety risks.

By contrast, continuous chromium plating systems adopt a modern approach, where parts move horizontally, in an automated flow, through a sequence of baths dedicated to degreasing, rinsing, electrochemical pickling, chromium plating and passivation. This strictly controlled sequence enables the chromium layer to be deposited uniformly, constantly and without major defects, due to the use of circular anodes and precise kinematic guidance systems. The key advantages of this plant type include high productivity, constant deposition quality, reduction of material losses and increased current efficiency. Furthermore, the integration of chromium vapor collection and treatment systems, along with the use of enclosed baths, significantly reduces the environmental impact and the operators' health risks.

On the other hand, continuous chromium plating is not without limitations. Initial investment costs are considerable, and implementing such a plant requires adapting the production flows and standardizing part dimensions. Flexibility is lower compared to traditional chromium plating, since continuous plants are optimized for large batches and for parts of uniform lengths, conditions rarely meet in diversified production. In addition, the complexity of kinematic mechanisms and automation require a high level of maintenance and technical expertise, which may pose a challenge for small and medium-sized enterprises.

In conclusion, it can be stated that traditional and continuous plating systems should not be regarded as antagonistic solutions but rather as complementary technologies, each tailored to specific industrial needs. Traditional chromium plating remains preferable for workshops dealing with small batches, varied parts, or non-specialized production, where flexibility and low implementation costs are priorities. By contrast, continuous chromium plating is the optimal choice for mass production, where uniformity, energy efficiency, and environmental protection outweigh versatility. The choice of the appropriate process essentially depends on part size, the production volume, and the technological infrastructure available within the enterprise.

Consequently, the future of industrial chromium plating lies not in replacing one method with the other, but in their rational integration according to the technological and economic context of each manufacturer.

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