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Review

A review of electroless coatings on non-metals: Bath conditions, properties and applications

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Abstract

The electroless coatings on the non-metal surface possess the desired properties for various applications in the aerospace, marine, medical, automotive, textile, electronics, household and food industries. Many researchers have developed the coating on non-conducting materials for many applications, and it has established its potential since its invention. This review started with fundamentals and their historical backgrounds. The work carried out on polymer, glass and ceramics is crtically reviewed. The optimized bath conditions developed for coating on the various non-metal substrates are populated for reference to future research works. The various properties of the developed coating, such as tribological, mechanical, electrical, and thermal, are addressed in line with their applications. The most recent applications of electroless coating on non-metals are reviewed. Finally, the future application of the electroless coating in emerging technologies is also discussed.

Introduction

Electroless plating, also known as autocatalytic plating, is a process that involves the deposition of a metal coating onto a substrate without the use of an external electric current. The essential components required for electroless plating are substrate, metal ions, reducing agent, complexing agent, pH buffer, and catalyst. Substrate: The substrate is the material onto which the metal coating is deposited. It can be made of various materials, such as plastic, ceramic, glass, textile, or metal. Metal ions: The metal ions are the metal source that will be deposited onto the substrate. They are typically provided as a solution containing the metal ions and other chemicals necessary for the plating process. Reducing agent: The reducing agent is a chemical that reduces the metal ions in the solution to their metallic form. The reducing agent is typically added to the plating solution as a salt or other compound. Complexing agent: The complexing agent is a chemical that helps to keep the metal ions in solution and prevents them from precipitating out. It also helps to control the rate of the plating process. pH buffer: The pH buffer is a chemical that helps to maintain a stable pH in the plating solution. This is important because the plating process is pH-dependent, and changes in pH can affect the rate and quality of the plating. Catalyst: The catalyst is a material that promotes the reduction of metal ions by the reducing agent. The catalyst is typically a metal, such as nickel, palladium, or copper, deposited onto the substrate in a separate step before plating.

Any material surface's physical and mechanical properties dictate its suitability and adaptability against physical damages, corrosive environment, bacterial activity, wear, and erosive surroundings. Hence numerous surface modifications are performed to achieve specific functionalities in the non-metals. The ability to deposit uniform thickness and shape and the inherent remarkable wear corrosive resistance and excellent weldability enable several industries to embrace electroless-based coatings for various applications [1]**.** Surface modification through various chemical and physical methods is required to achieve high-grade specific properties for diverse applications. Various surface modifications are made via hardening, ageing, and coating processes to achieve superior surface properties. Coatings are widely accepted in multiple industries due to their irresistible appearance, superior properties, and modern functionalities [2] in the non-metals.

The surface strength and stability are further enhanced by depositing metal, alloy, polymer, ceramic, and second-phase materials in micro and nanoscales. Electroless deposition is a coating process that deposits pure metals, alloys, or composites on a substrate material through autocatalytic reduction of metal ions in a chemical bath containing a suitable reducing agent. As a result, regardless of its conductivity, most substrate materials, having either complex profiles or irregular shapes, are coated [3]. The electroless coating is a distinct process that works even without an external electrical current. Other energy sources could also be used to maintain the heat in the water bath, such as fire or burning gas and oil. It is similar to galvanic-induced deposition and contact deposition. Electroless coatings enable the co-deposition of various second-phase particles powdered to micron and submicron sizes in the NiP matrix to enhance or modify the target surface's desired functionality, such as physical, magnetic, optical, and electrical properties [4], [5]. In 1835, Leibeg proposed electroless deposition, and in 1844, Wurtz observed the first nickel deposition from an aqueous salt bath containing hypophosphite ions. However, following the publication of Brenner and Riddels's successful 1946 report, widespread acceptance of EN deposition in various industries increased exponentially [6]. Since then, numerous scholars have contributed significantly to the field by reporting on the feasibility of depositing metallic particles on various substrates. Depending on the specific surface requirements, the deposits can be tailored as monolithic, alloyed, or co-deposited with single or multiple second-phase particle coating materials. Due to the participation of reducing agents and other bath additives in the autocatalytic reaction during the process, most metallic-based coatings are deduced as alloys with varying compositional ratios. The matrix's phosphorus content (in electroless nickel) largely determines the metallurgical characteristics of deposits in electroless coatings. As a result, Ni-P coatings are classified into three categories based on their phosphorus content: low (1–7%), medium (7–10%), and high (10–12%). The high phosphorus content of the coated surface is well-known for its superior anti-corrosive and wear-resistance properties [7]. EN composites incorporate submicron second-phase particles into an electroless metal/alloy matrix. Due to its unique and nanoscale effects, this composite surface demonstrates exceptional physical, mechanical, and functional properties distinct from bulk material [8]. Furthermore, co-deposition is likely achieved for some metals that cannot be deposited in an electroless way independently by combining with an electroless supporting metal. Mazaheri et al. [9] incorporated diamond particles to create coatings with high hardness, lubricative, anti-corrosive characteristics, and low wear rate. Different second-phase particles perform differently depending on their functional suitability. When superior hardness and low wear are required in the coated surface, Al_2O_3 [10], SiC [11], B_4C [12], [13], diamond [14], and WC [9] are preferentially added. Nevertheless, this review article focuses on non-metal depsotion of the electroless, which was not substantially reviewed so far.

Metal deposition on the plastic surface is accomplished in two ways: a) enhanced physical anchorage caused by the roughness and porosity of the plastic surface, and b) adhesion induced by the chemical kinetics of the surface constituents. Hence, prior to electroless deposition on plastics, pre-treatment is required. Surfactants are added to the electroless bath to prevent the electroless from amalgamation and maintain their thermodynamic stability [15]. Xiaohui Zheng et al. [16] employed laser surface texturing (LST) on the alumina surface to activate the electroless nickel deposition and showed that the laser textured based texturing of alumina before the electroless coating resulted in superior adhesiveness between the deposition and the alumina surface. Yongjun Zhang et al. [17] employed the implantation of spherical-shaped nano Ni-P particles on the surface of magnesium titanate ceramic surface through soaking in the electroless bath containing the nickel sulphate and sodium hypophosphite as nickel source and reducing agent along with the introduction of sodium borohydride for the initial deposition process. They successfully deposited the smooth silver (Ag) on the ceramic surfaces. The study concludes that the surface activation achieved through the Ni-P deposits on the surface achieved superior Ag coatings than the traditional Ni-B-based and classical activation processes. Xing Dang et al. [18] proposed a non-destructive activation process to reduce the damage to the alumina surface without using highly corrosive drugs and noble metals. Through the experimental results, the authors have successfully attached nickel particles on the ceramic surface, which act as the initiating points for the electroless phosphorous deposition.

The number of research articles published under the five major research areas in electroless non-conducting (non-metals) materials such as ceramics, glass, fibres, plastics, and polymers is shown in Fig. 1. It depicts that more research is directed towards ceramics for high-temperature applications through the electroless route. Various coatings are developed on glass for solar applications to improve the conductivity and reflectivity of UV rays. To improve the bonding between the matrix and reinforcement, the coating is done on the fibres, plastics and polymer materials [19]. Based on this survey, it is concluded that worldwide research is progressing in the chemical coating, especially in the electroless coating of non-conducting materials.

Based on SCOPUS database, the extensive research is going on in electroless coating for various purposes over the last 10 years is shown in the Fig. 2. Even though the electroless route is was discovered in the year 1944 by Brenner and Riddell [20]. The application of the electroless coating changing its dimension to reach the numerous sector for materials improvement is expanding. Nearly, 20500 documents related to electroless plating are published in SCOPUS database from the year 2012–2022. In electroless domain, 93000 patents are published all over the world whereas in research database around 9000 articles are available. Our focus in this research article is on non-conducting materials, thus the data of the published papers are collected from the database as 2037 in ceramics, 1588 in glass, 565 in fibres, 854 in polymer, 462 in Plastic, 52 in wood, 49 in rubber. Thus, it is essential to review the recent studies of electroless coating on the non-conduction materials.

Section snippets

Electroless coating on non-conducting materials

Due to its functional capabilities, ceramic alumina is widely used in various engineering applications such as mechanical, aerospace, biomedical, and architecture [21]. Various surface metallization processes are used to expand its application possibilities. Electroless deposition stands out due to its inherent advantages, including low cost, ease of fabrication, and superior surface properties [21]. The substrate must contain catalytically active sites to initiate the deposition using an…

Electroless coating bath conditions for various non-conducting surfaces

As discussed earlier, electroless plating is employed on various non-conducting materials such as reinforcement material of the polymer matrix and metal matrix composites, ceramic, glass, wood, fabrics, and rubber materials. The bath conditions used for making the coating over a range of substrates are discussed in Table 1, Table 2, Table 3, Table 4, Table 5.…

Morphology, weight gain and thickness

Fan et al. [106] studied the effect of loading Zirconia Toughened Aluminium particles (ZTA) in the electroless plating bath and the temperature change affecting the weight gain ratio of the nickel-plated coating and the loading capacity. The weight gain ratio is 13.4% for a loading capacity of 15 g/l, which is the maximum in the report. Further, the optimum operating temperature of 85 °C gives a maximum 12.9% weight gain ratio. The cauliflower structure of electroless Ni-P morphology, as shown…

Ongoing applications in the electroless coating

Electroless nickel plating is used to provide protection from wear and abrasion, resistance against corrosion, and to add hardness to parts of all conditions. It is commonly used in engineering, aerospace, oil and gas, construction, electronics and several other avenues in coatings applications. However, the recent applications of the electroless Ni-P coating are populated in Table 6.…

Challenges and opportunities

The coating on metallic and non-metallic surfaces involves many challenges, from the selection of chemicals to the selection of substrate. Environmental conditions and level of parameters should be appropriately identified for its application. Finalizing process parameters for many existing and new coatings is challenging, especially when nanomaterials are involved. The grey areas in the electroless coating are provided based on the author's experiences, and in future, the scholars will focus…

Conclusions and future scope

This review article details coating parameters used for electroless coating on various non-conducting materials. The deposition time, bath temperature, salt concentration, wetting agent and surface activation impact the deposition rate. The selection of the pre-treatment process is highly suggested to attain better adhesion with the substrate through effective activation methods. The potential application of electroless plating is expanding in numerous ways with improved properties such as…

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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