

Research Progress and Application Prospects of Micro-arc Oxidation Technology for Magnesium Alloys

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Abstract

As a lightweight high-performance metallic material, magnesium alloys demonstrate significant application potential in fields such as aerospace, automotive manufacturing, and biomedical engineering. However, their high chemical reactivity leads to susceptibility to corrosion and degradation in service environments, severely limiting their engineering applications. Micro-arc oxidation (MAO) technology, also known as plasma electrolytic oxidation (PEO), effectively addresses the corrosion protection of magnesium alloys by in-situ generating a ceramic oxide layer on the metal surface. This paper systematically elaborates on the fundamental principles, process optimization, coating performance enhancement, and multidisciplinary applications of micro-arc oxidation technology for magnesium alloys. It comprehensively analyzes the current research status and development trends of this technology, providing theoretical guidance and technical references for the surface modification of magnesium alloy materials.

Keywords

Micro-arc Oxidation, ZK60 Magnesium Alloy, Process Parameters, Application.

1. Introduction

With the rapid development of modern industries, the demand for lightweight structural materials has significantly increased, particularly in aerospace, transportation, and biomedical engineering. Magnesium alloys are regarded as one of the most promising lightweight metallic materials owing to their extremely low density, high specific strength, excellent thermal conductivity, and favorable recyclability. In addition, their good biocompatibility makes them attractive candidates for biomedical implants. Consequently, magnesium alloys have attracted considerable attention for applications in aerospace structures, automotive components, and degradable medical devices, and are widely considered key materials for next-generation lightweight engineering systems. Despite these advantages, the practical application of magnesium alloys is severely restricted by their poor corrosion resistance. Magnesium exhibits a very negative standard electrode potential (approximately -2.37 V), which makes it highly susceptible to electrochemical corrosion in humid or saline environments. Furthermore, the naturally formed oxide film on magnesium surfaces is loose, porous, and weakly bonded to the substrate, offering limited protection against aggressive media. As a result, rapid degradation of mechanical integrity may occur during service. Therefore, developing efficient surface modification techniques is essential to improve the durability and reliability of magnesium alloys.

Various surface treatment technologies have been developed for magnesium alloys, including chemical conversion coatings, anodizing, electroplating, and thermal spraying. Among them, micro-arc oxidation (MAO), also referred to as plasma electrolytic oxidation (PEO), has emerged as one of the most promising approaches. MAO involves the generation of plasma micro-discharges on the metal surface under high voltage in an electrolyte solution, leading to the in-situ formation of a ceramic oxide coating strongly bonded to the substrate. Compared with conventional surface treatments, MAO coatings exhibit superior hardness, excellent adhesion, and improved corrosion resistance. These characteristics make MAO particularly suitable for enhancing the surface performance of magnesium alloys.

In recent years, extensive studies have been devoted to understanding the discharge behavior, coating formation mechanism, and process optimization of MAO coatings on magnesium alloys. Moreover, increasing attention has been paid to the development of multifunctional coatings with enhanced wear resistance, corrosion resistance, and bioactivity. Nevertheless, several challenges remain, including the control of coating porosity, improvement of coating uniformity, and reduction of processing energy consumption. In this context, a comprehensive understanding of the underlying mechanisms and process parameters is crucial for advancing MAO technology toward practical applications. This review summarizes the recent progress in micro-arc oxidation of magnesium alloys, focusing on the fundamental mechanisms of coating formation, the influence of processing parameters, and strategies for performance optimization. The current applications and future development trends of MAO coatings are also discussed.

2. Fundamentals of Micro-Arc Oxidation on Magnesium Alloys

Micro-arc oxidation is a complex surface modification process involving electrochemical reactions, plasma discharge phenomena, and high-temperature oxidation. When a sufficiently high voltage is applied to a metal substrate immersed in an electrolyte, the initially formed anodic oxide film undergoes dielectric breakdown, resulting in numerous plasma micro-discharges across the surface. The temperature within these discharge channels can reach 1000–2000 °C, accompanied by extremely high local pressures [1]. Under such extreme conditions, both the substrate metal and electrolyte components participate in chemical reactions, leading to the formation of ceramic oxide phases such as MgO, Mg₂SiO₄, and Mg₃(PO₄)₂ [2].

The MAO process generally proceeds through several stages, including the initial anodic oxidation stage, spark discharge stage, stable micro-arc discharge stage, and finally an arc discharge stage as the coating thickens. During the early stage, a thin oxide film forms on the magnesium surface. As the applied voltage increases, local dielectric breakdown occurs, producing numerous sparks. With continued oxidation, the process enters a stable micro-arc discharge regime in which molten oxide materials are repeatedly ejected from discharge channels and rapidly solidified in the electrolyte [3]. The resulting MAO coating typically exhibits a characteristic multilayer structure consisting of a porous outer layer and a dense inner barrier layer. The outer layer forms mainly through the rapid solidification of molten materials expelled from discharge channels, whereas the inner layer grows via inward diffusion and oxidation reactions. The dense inner layer plays a crucial role in determining the corrosion resistance of the coating [4]. For example, MAO treatment of AZ63 magnesium alloy in NaAlO₂ electrolyte for 20 min can produce coatings with a thickness of approximately 37 μm and significantly improved corrosion resistance [5]. The plasma discharge behavior strongly influences the microstructure of MAO coatings. Factors such as electrolyte composition, electrical parameters, and alloy composition determine the intensity and distribution of micro-discharges. For instance, when AZ31 magnesium alloy is treated in a phosphate–silicate electrolyte containing K₂ZrF₆, the discharge sparks gradually evolve from fine and uniformly

distributed to larger and more concentrated sparks with increasing treatment time, resulting in changes in coating porosity and morphology [6].

Furthermore, each micro-arc discharge typically lasts only several tens of microseconds, yet the energy density within the discharge channel can reach approximately 10^6 W/cm^2 [3]. Under these conditions, molten oxide materials undergo rapid quenching, forming characteristic “pancake-like” structures on the coating surface. The periodic opening and closure of discharge channels lead to a layered growth mode, which contributes to the formation of a lamellar microstructure and improves the resistance of the coating to crack propagation [1]. The chemical composition of the substrate also affects the coating formation process. Aluminum, a major alloying element in many magnesium alloys, promotes the formation of Al_2O_3 phases within the coating. Consequently, AZ91 alloy generally forms denser MAO coatings than AZ31 due to its higher aluminum content [1]. In addition, rare-earth elements such as Y and Nd in WE-series magnesium alloys can form stable oxides that regulate discharge behavior and improve coating uniformity [7]. Electrolyte composition is another key factor determining coating structure and properties. Silicate-based electrolytes tend to produce coatings with high hardness due to the formation of Mg_2SiO_4 phases, whereas phosphate-based electrolytes often yield bioactive coatings containing $\text{Mg}_3(\text{PO}_4)_2$ phases[2]. By adjusting the electrolyte composition, the microstructure and functional properties of MAO coatings can be effectively tailored.

3. Process Regulation and Performance Optimization

The properties of MAO coatings are strongly influenced by processing parameters, including electrical parameters, substrate condition, and electrolyte composition. Among these factors, electrical parameters such as voltage, current density, pulse frequency, and duty cycle play dominant roles in controlling discharge intensity and coating growth. Voltage directly determines the breakdown of the oxide film and the energy of micro-discharges. Increasing the applied voltage generally leads to thicker coatings due to more intense plasma discharge; however, excessively high voltage may result in the formation of large pores and microcracks within the coating [8]. Similarly, current density affects the growth rate and morphology of the coating. High current density combined with short processing time often produces relatively dense coatings, whereas prolonged treatment may increase coating thickness but also enhance porosity [9]. Pulse parameters also have a significant influence on coating characteristics. Adjusting the pulse frequency and duty cycle can modify discharge duration and energy distribution, thereby affecting surface roughness and pore size. For example, MAO coatings produced at a frequency of 1000 Hz and a duty cycle of 50% exhibit significantly reduced surface roughness [10]. Therefore, careful optimization of electrical parameters is necessary to achieve coatings with desirable microstructure and performance.

The initial condition of the magnesium substrate is another important factor affecting MAO behavior. Heat treatment can alter the microstructure and distribution of second-phase particles, which in turn influences discharge activity during oxidation. For instance, AZ31 alloy subjected to T4 solution treatment typically produces more uniform MAO coatings than T6-aged samples due to the reduced presence of precipitates [11]. Surface pretreatment methods such as sandblasting, chemical etching, and laser texturing can also modify surface roughness and energy, thereby improving coating adhesion and uniformity [12–14]. Electrolyte design plays a crucial role in tailoring coating performance. Conventional silicate and phosphate electrolytes remain widely used because they allow stable discharge and formation of protective oxide phases. Nevertheless, recent studies have focused on developing composite electrolyte systems containing functional additives. The addition of K_2ZrF_6 to silicate-phosphate electrolytes, for example, significantly improves corrosion resistance by promoting

the formation of dense oxide phases [6]. In addition to traditional electrolytes, environmentally friendly systems are increasingly being explored. The use of deep eutectic solvents (DES) and other green electrolytes has attracted considerable interest because they can reduce environmental pollution while maintaining desirable coating performance [15]. Furthermore, advanced functional coatings incorporating layered double hydroxides (LDHs) or metal-organic frameworks (MOFs) have been reported to provide self-healing capabilities and enhanced corrosion protection [16-18].

4. Applications and Future Perspectives

The unique structural and functional characteristics of MAO coatings make them highly attractive for a wide range of applications. In aerospace and automotive industries, MAO coatings significantly improve the corrosion resistance and wear resistance of magnesium alloy components, thereby extending their service life in harsh environments. For example, MAO coatings can effectively protect lightweight magnesium alloy structures used in aircraft and high-performance vehicles. In the biomedical field, MAO coatings have shown considerable potential for improving the bioactivity and degradation behavior of magnesium alloys. By incorporating calcium, phosphorus, or strontium into the electrolyte, bioactive coatings containing hydroxyapatite-like phases can be formed, which enhance cell adhesion and bone integration. Such coatings are particularly promising for biodegradable orthopedic implants and cardiovascular devices.

Despite the significant progress achieved in recent years, several challenges remain for the practical application of MAO technology. The inherent porosity of MAO coatings can reduce corrosion resistance if not properly controlled, and the high energy consumption of the process may limit industrial scalability. In addition, further research is required to improve coating uniformity on complex-shaped components. Future studies should therefore focus on several key aspects. First, advanced in situ characterization techniques should be employed to better understand plasma discharge mechanisms and coating growth behavior. Second, the development of multifunctional composite coatings with improved corrosion resistance, wear resistance, and bioactivity remains an important research direction. Finally, the design of environmentally friendly electrolytes and energy-efficient MAO processes will be essential for achieving sustainable industrial applications.

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