Preparation and Innovative Design Applications of Paper-Based Aluminized Film

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Abstract: The growing demand for sustainable and innovative materials in product design has spurred interest in unconventional resources. Despite this, a gap persists in the effective utilization of paper-based materials, particularly with metallic coatings, for creative applications. This study aims to address this by exploring the technical methods for applying Aluminum (Al) coatings to paper substrates. We developed paper-based aluminum coatings and combined them with corrugated cardboard to create a novel material for product development. Utilizing high-strength specialty paper as the substrate, an orthogonal experiment was conducted to identify key process parameters. Factors such as target–substrate distance, working pressure, current intensity, and coating duration were evaluated for their impact on the properties of the Al film. Our research culminated in the production of high-quality Al-plated corrugated cardboard. Capitalizing on its unique attributes, we employed a design approach that led to the creation of innovative furniture featuring structural forms like folding and insertion. This study not only introduces a new range of Al-plated corrugated cardboard products but also expands the potential applications of paper-based aluminized film in material-based product design.

Keywords: paper substrate coated with Al film; aluminized film; corrugated paperboard; creative furniture design

1. Introduction

The global scarcity of wood resources has become a pressing concern for nations worldwide. In response, many countries are actively seeking recyclable, eco-friendly, and easily processable raw materials to bolster their raw material economies. In 1858, British and German researchers discovered the sputtering phenomenon in the laboratory. Although it had a slow developmental process, by 1877, the vacuum sputtering deposition of thin films was successfully achieved. Xu et al. (2009) report that many metal oxides are used for coating, including MgO, TiO2, SiOx, Al2O3, etc. Among them, alumina (Al2O3) materials deposited on surfaces offer unique advantages in optics, electronics, machinery, packaging, and other areas [1]. Therefore, research into the crucial technology of paper-based Aluminum (Al) coating has paved the way for the production of Al-coated corrugated boards. Characterized by their moisture resistance, fire resistance, cost-effectiveness, and versatility, these Al-plated corrugated boards are emerging as ideal materials for creative furniture, packaging, and innovative product designs. Such products not only meet market demands but also offer substantial economic returns for businesses.

2. Vacuum Magnetron Sputtering Coating Mechanism

To date, Al film formation has been categorized into three primary methods: physical vapor deposition, the chemical vapor deposition method, and the sol-gel method. These
methods involve vaporizing the coating material through evaporation or sputtering and depositing it onto the substrate surface to form a film. Solid sediment film formation transpires due to the chemical reaction between a gaseous substance and a solid surface. Through heat treatment, a compound solid emerges, either as a metal-organic or inorganic compound, via solution or sol–gel processes, subsequently solidifying into a film. Different film-forming methods produce varied aluminum (Al) plating effects, and each has its distinct sub-methods. The magnetron sputtering deposition method utilized in this paper belongs to the physical vapor deposition category. One of its advantages over other methods is the enhanced control over the individual components of the object. Additionally, low-temperature and high-speed sputtering ensure a strong bonding force with the substrate, resulting in a fine and uniform coating. This makes it suitable for the growth of surface films on materials [2,3]. The purpose of this study is to investigate magnetron sputtering deposition technology in order to promote the diversified development of furniture materials. The aim is to create new furniture materials by preparing paper-based Al film and Al-plated corrugated board. The vacuum magnetron sputtering Al plating technology involves the preparation of a new type of Al thin film material with high barrier properties. In this process, DC power supply is used as the sputtering energy source, high-strength specialty paper serves as the base material, and pure Al is used as the target material. During sputtering, the inert gas undergoes ionization by the current from the DC power supply, leading to the generation of positive ions via electron–ionization interactions. These positive ions impinge upon the target at high velocities. Rather than directly sputtering atoms, the target surface transfers momentum to the colliding atoms, facilitating energy exchange and deposition of the paper-based Al film. The sputtering process relies on glow discharge, as the sputtering ions originate from gas discharge [4].

3. Necessary Conditions for Preparation of Al Film on a Paper Substrate

3.1. Selection of Paper Base

Using DC magnetron sputtering, an Al film was deposited onto a paper substrate to prepare aluminized corrugated paperboard. The experiment involved testing the physical properties of high-strength specialty paper-based materials. For the experiment, papers of varying weights, from 120 g to 250 g, were selected. Pure wood pulp served as the raw material, leading to a uniform paper fiber structure, minimal stretching, high strength, diverse textures and patterns, and favorable physical properties.

Weight variations influenced slight alterations in pH value, tensile strength, and deformation temperature. The chosen high-strength specialty paper exhibited a pH range of 8.0 to 9.5, a tensile strength greater than or equal to 70 N/15 mm, and moisture content between 4% and 9%. With a deformation temperature ranging from 100 °C to 120 °C, the paper could be used continuously within this range, making it an ideal non-metallic coating substrate.

3.2. Screening of Key Preparation Process Parameters by Orthogonal Experiment

The experiment utilized a Plackett–Burman design with \( N = 12 \) to identify eight essential parameters in DC magnetron sputtering. The parameters included base target spacing, working pressure, winding speed, dust removal time, current intensity, coating time, pre-sputtering time, and background vacuum. Furthermore, three virtual factors were incorporated, with each variable set at two specific levels. A total of twelve experiments were executed to assess the impact of each factor.

Table 1 presents the levels of the Plackett–Burman design factors contributing to the deposition rate. Table 2 details the results of the experimental design.
Table 1. Plackett–Burman design factors.

<table>
<thead>
<tr>
<th>Influencing Factor</th>
<th>Base Target Spacing (mm)</th>
<th>Working Air Pressure (Pa)</th>
<th>Winding Speed (m/min)</th>
<th>Dust Removing Time (min)</th>
<th>Current Intensity (A)</th>
<th>Plating Film Time (min)</th>
<th>Pre-Sputtering Time (min)</th>
<th>Background Vacuum Degree (10^3 Pa)</th>
<th>Virtual Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>L</td>
<td>40</td>
<td>0.1</td>
<td>1</td>
<td>6</td>
<td>1.5</td>
<td>10</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>B</td>
<td>H</td>
<td>100</td>
<td>0.9</td>
<td>4</td>
<td>36</td>
<td>4.5</td>
<td>30</td>
<td>60</td>
<td>-</td>
</tr>
</tbody>
</table>

Following a statistical analysis of the experimental data, Table 3 presents the outcomes of the Plackett–Burman experiment. For instance, considering factor A representing the target spacing, the data reveal that the deposition rate diminishes as the base target spacing increases, with an associated influence level of −0.17. This indicates an inverse relationship between the substrate–target distance and deposition rate. Consequently, it is advisable to select an appropriate base target spacing for the practical deposition of Al film in the creation of paper-based composites, or for use in subsequent factor optimization experiments.

Table 2. Plackett–Burman design experiment results.

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>J</th>
<th>K</th>
<th>L</th>
<th>Deposition Rate (nm/min)</th>
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</thead>
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<tr>
<td>1</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
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</tr>
<tr>
<td>2</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
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<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
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</tr>
<tr>
<td>3</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
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</tr>
<tr>
<td>4</td>
<td>L</td>
<td>H</td>
<td>L</td>
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<td>L</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>L</td>
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</tr>
<tr>
<td>5</td>
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<td>L</td>
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<td>L</td>
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<td>H</td>
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<td>L</td>
<td>L</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>1.99</td>
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<tr>
<td>9</td>
<td>H</td>
<td>H</td>
<td>H</td>
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<td>L</td>
<td>H</td>
<td>H</td>
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</tr>
<tr>
<td>10</td>
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<td>L</td>
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<td>H</td>
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<td>H</td>
<td>H</td>
<td>2.96</td>
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<tr>
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<td>L</td>
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<tr>
<td>12</td>
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<td>L</td>
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<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>1.37</td>
</tr>
</tbody>
</table>

Table 3. Plackett-Burman analysis of experimental results.

<table>
<thead>
<tr>
<th>Factor</th>
<th>Importance</th>
<th>Level of influence</th>
<th>Quadratic Sum</th>
<th>Contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Y</td>
<td>Y</td>
<td>-0.17</td>
<td>15.40</td>
</tr>
<tr>
<td>B</td>
<td>Y</td>
<td>Y</td>
<td>-0.15</td>
<td>28.42</td>
</tr>
<tr>
<td>C</td>
<td>N</td>
<td>Y</td>
<td>0.078</td>
<td>2.72</td>
</tr>
<tr>
<td>D</td>
<td>N</td>
<td>N</td>
<td>0.057</td>
<td>1.14</td>
</tr>
<tr>
<td>E</td>
<td>Y</td>
<td>N</td>
<td>0.33</td>
<td>36.71</td>
</tr>
<tr>
<td>F</td>
<td>N</td>
<td>N</td>
<td>0.15</td>
<td>10.78</td>
</tr>
<tr>
<td>G</td>
<td>N</td>
<td>N</td>
<td>-0.023</td>
<td>1.78</td>
</tr>
<tr>
<td>H</td>
<td>N</td>
<td>N</td>
<td>0.051</td>
<td>0.94</td>
</tr>
<tr>
<td>J</td>
<td>N</td>
<td>N</td>
<td>0.0058</td>
<td>0.08</td>
</tr>
<tr>
<td>K</td>
<td>N</td>
<td>N</td>
<td>0.0055</td>
<td>1.18</td>
</tr>
<tr>
<td>L</td>
<td>N</td>
<td>N</td>
<td>0.049</td>
<td>0.85</td>
</tr>
</tbody>
</table>

The factor A’s sum of squares percentage stands at 15.40%, marking it as a significant influencing factor. Ranked third in sum of squares, this underscores the importance of the analysis findings. Additionally, as presented in Table 3, the primary influential factors are the base target spacing (A), working pressure (B), current intensity (E), and coating time (F), with impact values of 15.40%, 28.42%, 36.71%, and 10.78%, respectively. The virtual factors exhibit limited influence, attesting to the accuracy of the aforementioned experiments.
Narrowing down the Plackett–Burman influential factors, we identify four primary elements affecting the deposition rate: target–substrate distance, working pressure, current intensity, and coating time [5–8].

4. Key Technology of Paper-Based Aluminized Film

The vacuum magnetron sputtering technology used for Al film deposition is intricate and encompasses numerous variables. After pinpointing influential factors via Plackett–Burman screening, we examined more closely the primary determinants of the deposition rate. Factors such as target–substrate distance, working pressure, current intensity, and coating time were subjected to detailed scrutiny in individual experimental studies. The resulting experimental data were then graphically represented in relevant curve diagrams, facilitating comprehensive analysis. The goal of this approach was to produce a paper-based Al film in line with the set design criteria.

4.1. Target Substrate Distance

The separation between the target surface and the paper substrate surface, termed as the target–substrate distance, is a critical parameter in the DC magnetron sputtering coating process. While varying the target–substrate distance does not affect the sputtering coefficient, it notably alters the deposition rate of the Al coating and its application uniformity [9–11]. Lengthening the target–substrate distance prolongs the journey of the material source particles to the paper substrate, thereby decreasing the deposition rate. This outcome results from fewer particles reaching the paper-based surface due to the increased distance. Thus, carefully increasing the target-to-substrate distance can reduce potential collisions with other gas molecules, improving the coating’s uniformity [12].

4.1.1. Experimental Methods

The selected base material, a high-strength specialty fabric paper derived from pure wood pulp, was procured from Shandong Huatai Paper Co., Ltd. Sourced from Zhongnuo New Material (Beijing) Technology Co., Ltd. (Beijing, China). The rectangular target was crafted from 99.999% pure Al and measured 600 mm × 120 mm. The target exhibited a thickness of 8mm and was positioned with precision at the center of the target material plane. This enabled the acquisition of parameters influencing the deposition rate of the aluminized film during the sputtering process, with the objective of determining the optimal base target spacing.

The experimental process utilized a JRJ-400 winding magnetron sputtering coating machine provided by Beijing Dongfang Gaide Vacuum Technology Co., Ltd. (Beijing, China). Following this, a Hitachi S4800 scanning electron microscope (Tokyo, Japan) was employed to analyze the surface morphology of the Al film.

4.1.2. Influence of Target Base Distance on Deposition Rate of Paper-Based Aluminized Film

For the experiment, a rectangular target was selected due to its crucial features that ensure sputtering stability and superior coating quality. Figure 1 illustrates the deposition layout of the target material, with the base target spacing oriented along the z-direction. This graph captures the variations in deposition rate in relation to the x and z coordinates.
Figure 1. Target deposition plane diagram.

The substrate–target distance plays a pivotal role in determining the deposition rate on the target surface. Notably, as this distance increases, the deposition rate experiences a decrease. This results in inconsistent uniformity of the Al film deposited on the paper substrate. Adjusting and determining an appropriate substrate–target distance is imperative to ensure uniform performance across different sections of the paper-based Al plating.

In the sputtering process, the typical target–substrate distance lies between 60 and 80 mm, given that sputtering particles usually have an average free path under 100 mm. Considering the sputtering process’s glow plasma discharge characteristics, we chose an experimental target base distance of 70 mm.

Furthermore, the paper base’s transmission speed within the coating area was set between 2.20 and 12.16 m/min. The thickness of the Al film was measured using the HP-CHY-L aluminized film thickness gauge from Jinan Hengpin Electrical and Mechanical Technology Co., Ltd. (Jinan, China), yielding a thickness of 490 nm. The barrier properties of the Al film were evaluated using two methods simultaneously. The first involved using the OX-TRAN Model 2/21 oxygen permeameter, utilizing a high-precision Coulomb electric quantity sensor to analyze oxygen permeability and the electrical properties of polymer barrier materials. The second approach utilized the PERMATRAN-W Model 1/50 water vapor transmittance tester. This tester sets controlled humidity (RH) levels, enabling direct insights into the Al film’s barrier quality during standalone machine operations and presenting the test process curve.

4.2. Working Air Pressure

During the fabrication of paper-based Al-coated magnetron sputtering, the operational pressure environment is governed by two key factors. These factors are the working vacuum level achieved by adjusting the volume of Ar gas and the background vacuum level attained within the vacuum chamber prior to sputtering. Throughout the experiment, adjustments to the working pressure were made by altering the Ar gas flow rate, and the background vacuum was consistently maintained at $10^{-3}$ Pa [13–15].

4.2.1. Experimental Methods

Due to its superior ionization rate relative to other gases, Argon (Ar) gas is the preferred ion gas source for target bombardment. Being a monatomic inert gas, Argon plays a pivotal role in the deposition of the Al film in DC magnetron sputtering. In this experiment, the sputtering current was set at 2A, the Ar gas flow rate was adjusted, the sputtering time was maintained at 35 min, and the background vacuum was set to $1.0 \times 10^{-2}$ Pa. The impact of the Ar gas flow rate on barrier performance was further investigated.

4.2.2. Effect of Ar Flow Rate on the Thickness of Al Coating on a Paper Substrate

The operational conditions of working pressure are determined by factors like the Ar gas flow rate, making this factor crucial for controlling the thickness of the paper-based
Al film. The experiment reveals the relationship between the Ar gas flow rate and Al coating thickness across three stages: A, B, and C. As illustrated in Figure 2, during the A phase, a decrease in coating thickness from 90 nm to 80 nm is observed as the Ar gas flow rate is set at 85 sccm. Here, Ar ions effectively bombard the pure Al target, ensuring complete ionization and sputtering of Al atoms, thus yielding the highest deposition rate.

In the subsequent B phase, reducing the Ar gas flow rate from 75 sccm to 70 sccm results in a decline in the Al layer thickness from 80 nm to 20 nm. At this juncture, the deposition rate experiences a substantial decrease. As the Ar gas flow rate continues to decrease, the DC sputtering current fails to fully ionize the Ar gas, leading to an excessive volume of Ar gas that impedes sputtering particles from reaching the substrate, thus failing to enhance film barrier.

In the final C phase, as the Ar gas flow rate is further reduced, the deposition rate continues to decrease.

Figure 2. Relationship between Ar gas flow rate and aluminized film thickness. Stage A: Ar gas flow rate 85scm, Thickness [80,90] nm; Stage B: Ar gas flow rate [70,75] scm, Thickness [20,80] nm; Stage C: Ar gas flow rate is reduced, deposition rate decreases.

4.2.3. Effect of Ar Flow Rate on the Barrier Properties of Paper-Based Aluminized Film

The experimental results established a connection between moisture permeability, oxygen permeability, and Ar gas flow rate, as depicted in Figure 3. The findings are as follows:

1. As the Ar flow rate reduced from 85 sccm to 75 sccm, the Al film’s barrier properties exhibited a gradual decline. Moisture permeability and oxygen permeability increased from 0.46 g/(m² × atm × 24 h) and 2.08 cm³/(m² × atm × 24 h) to 0.5 g/(m² × atm × 24 h) and 2.28 cm³/(m² × atm × 24 h), respectively.

2. With a further decrease in the Ar flow rate to 70 sccm, the Al film’s barrier properties experienced a substantial deterioration. Moisture permeability and oxygen permeability escalated to 3.51 g/(m² × atm × 24 h) and 26.08 cm³/(m² × atm × 24 h), respectively.

3. Upon reducing the Ar flow rate to 65 sccm, the barrier properties of the Al film exhibited a minor decline once again. Moisture permeability and oxygen permeability demonstrated gradual increases, measuring 3.6 g/(m² × atm × 24 h) and 28.01 cm³/(m² × atm × 24 h), respectively.

4. The most substantial barrier properties, accompanied by the thickest film, were achieved at an Ar flow rate of 85 sccm. Moisture permeability and oxygen permeability were determined as 0.46 g/(m² × atm × 24 h) and 2.08 cm³/(m² × atm × 24 h), respectively.

As shown in Figure 3, the mutagenic nature of the relation curves between Ar flow rate, moisture permeability, oxygen permeability, and Al film thickness can be attributed to the deposition process occurring at diverse positions. The variations in barrier parameters stem from measurements of the thickness of Al plating coating prepared under distinct Ar partial pressures, as indicated in Figure 2.
Figure 3. Relationship between moisture permeability, oxygen permeability, and Ar flow rate.

In this experiment, the background vacuum is maintained at $1.0 \times 10^{-2}$ Pa, and the Ar gas flow rate is set at 85 sccm. As a result, the Al film exhibits satisfactory barrier properties, and its surface appears uniformly smooth.

4.3. Current Intensity

As a critical parameter in the process, the sputtering current plays a significant role in determining the state of increased incident ion energy. An escalation in ion energy is directly linked to a rise in sputtering particle energy, ultimately leading to an augmented deposition rate. This increase is driven by the elevation in both the sputtering coefficient and substrate temperature. However, it is important to note that an excessively high sputtering current can trigger a secondary sputtering effect, which in turn causes a decrease in the growth rate of the Al film.

This phenomenon can lead to weakened adhesion of the target Al ions to the substrate surface, resulting in a situation where the stripping of Al ions from the target is not firmly secured. The use of an excessively high sputtering current introduces multiple concerns. On one hand, the target—serving as the sputtering source—is bombarded by high-speed, high-energy ions and electrons, potentially leading to excessive ion injection and causing the target to overheat and melt. On the other hand, the impact of high-speed ions and electrons on the substrate can elevate the temperature to undesirable levels. This not only hampers the adhesion of the Al coating but can even result in the burning of the substrate material.

4.3.1. Experimental Methods

The relationship between different DC sputtering currents and moisture permeability, oxygen permeability, and Al film thickness was analyzed based on the PB experimental results. At a sputtering current of 3A, the moisture permeability is $0.50 \text{ g/(m}^2 \times \text{atm} \times 24 \text{ h)}$, the oxygen permeability is $4.08 \text{ cm}^3/(\text{m}^2 \times \text{atm} \times 24 \text{ h)}$, and the coating thickness is 76 nm. Conversely, at a sputtering current of 0.5A, the moisture permeability is $2.52 \text{ g/(m}^2 \times \text{atm} \times 24 \text{ h)}$, the oxygen permeability is $23.48 \text{ cm}^3/(\text{m}^2 \times \text{atm} \times 24 \text{ h)}$, and the coating thickness is 21 nm.

Consequently, an increase in sputtering current results in a uniform silver-gray appearance of the paper-based Al film. The Al target powder within the sputtering chamber emits a purple glow. This increase in sputtering current leads to alterations in moisture permeability, oxygen transmission rate, and plating thickness.

4.3.2. Effect of Current Intensity on Thickness and Barrier Properties of Aluminized Film on Paper Substrate

The experiment reveals the correlation between sputtering current and Al coating thickness. It is observed that Al coating thickness experiences changes as the sputtering
current varies. Sputtering initiates when the sputtering current reaches 0.25 A, establishing this value as the threshold current for target sputtering. With the continuous increase in current, the target’s surface current density also rises. Notably, as the sputtering current increases from 0.5 A to 2 A, a corresponding augmentation in plasma density within the sputtering chamber is evident. Consequently, the thickness of the plated Al film increases from 21 nm to 82 nm. This improvement positively impacts both the sputtering rate of the target and the deposition rate of the Al film.

Upon surpassing 2 A in sputtering current, the thickness of the Al film gradually decreases. This diminishing trend persists until the Al coating thickness reaches 76 nm, coinciding with a sputtering current of 3 A.

As the sputtering current increases from 0.5 A to 2.5 A there is a notable reduction in moisture permeability of the Al film, diminishing from 2.52 g/(m² × atm × 24 h) to 0.43 g/(m² × atm × 24 h), along with a decrease in oxygen permeability from 23.45 cm³/(m² × atm × 24 h) to 2.06 cm³/(m² × atm × 24 h). This change translates to a substantial enhancement in barrier properties. Upon further increasing the sputtering current from 2.5 A to 3 A, the moisture permeability of the Al film regresses from 0.43 g/(m² × atm × 24 h) to 0.50 g/(m² × atm × 24 h), while the oxygen transmission rate rises from 2.06 cm³/(m² × atm × 24 h) to 4.08 cm³/(m² × atm × 24 h).

It is evident that the moisture permeability and oxygen permeability of the Aluminized film initially undergo significant reductions before gradually increasing. This trend is a consequence of the sputtering current’s incremental rise. Referencing Figures 4 and 5, a sputtering current of 2 A corresponds to a coating thickness of 82 nm. Meanwhile, a sputtering current of 2.5 A results in a coating thickness of 78 nm, accompanied by an optimal Al film barrier performance.

![Figure 4](image1.png)

**Figure 4.** Relationship between sputtering current and plating Al coating thickness.

![Figure 5](image2.png)

**Figure 5.** Relationship between sputtering current and oxygen permeability of Al film plating.
4.3.3. Effect of Current Intensity on the Structure of Al Coating on Paper Substrate

Al films were produced under various current intensities within the range of 2 A to 2.5 A. Within this range, the barrier properties, moisture permeability, oxygen permeability, and thickness of the Al coating were evaluated. The results did not exhibit a consistent trend of simultaneous increase and decrease. Notably, the thickest aluminized film did not yield the best barrier properties. At a sputtering current of 2.5 A, the deposited aluminized film demonstrated a thinner profile compared with its 2 A sputtering current counterpart. However, this thinner film exhibited enhanced barrier performance, smoother surface quality, and improved evenness.

In the case of the 2 A sputtering current, the Al film surface displayed inadequate flatness and cracks. Additionally, a comparison between sputtering currents I = 2 A and I = 2.5 A revealed a decrease in aluminized film thickness from 82 nm to 78 nm. This reduction coincided with decreased moisture and oxygen permeability, decreasing from 0.47 g/(m² × atm × 24 h) and 2.10 cm³/(m² × atm × 24 h) to 0.43 g/(m² × atm × 24 h) and 2.06 cm³/(m² × atm × 24 h), respectively. This led to an improvement in barrier performance, which was corroborated by the surface morphology of the aluminized film displayed in Figure 6. Notably, the paper-based Al coating exhibited satisfactory results, as evident in Figure 7.

The experiment underscores the significance of sputtering current as a critical technical parameter influencing the Al film formation process. The judicious selection of an appropriate current value is the essential precondition and pivotal factor in achieving high-quality Al film.

![Figure 6. Surface morphology of Al coating prepared at current intensity I = 2.5 A.](image)

![Figure 7. Image of paper-based plating Al film effect.](image)

4.4. Effect of Coating Time on Paper-Based Al Film

Our research indicates that under consistent conditions, while other parameters remain unchanged throughout the coating process, a specific critical range of coating deposition thickness exists. Within this range, a correlation between barrier properties and film thickness is discernible. Notably, the barrier performance demonstrates a proportional relationship with increasing film thickness. However, upon surpassing this critical thickness, augmenting the film layer thickness has limited impact on barrier performance. Consequently, a blind increase in coating time may not necessarily enhance the film’s barrier properties.

The experimental findings reveal that optimal results are achieved when the coating time falls within the range of 45 to 80 min and a stable sputtering current is maintained at
2 A to 2.5 A. These conditions foster uniform sputtering across the target surface and lead to an expanded glow region. This, in turn, yields an ideal combination of deposited film thickness and Al film barrier effectiveness.

To ensure that the film barrier aligns with requirements, it is imperative to select the most suitable coating time based on specific needs and considerations.

### 4.4.1. Experimental Method

In the experiment, with a sputtering current of 2 A, an Ar gas flow rate of 80 sccm, and a background vacuum of $7.5 \times 10^{-3}$ Pa, the connection between coating time and the resulting Al film’s oxygen permeability, moisture permeability, and coating thickness was established. This relationship is illustrated in Table 4.

**Table 4.** The oxygen permeability, moisture permeability, and thickness of the Al film, prepared using different coating durations.

<table>
<thead>
<tr>
<th>Plating Film Time / (min)</th>
<th>Oxygen Transmission Rate / (cm$^3$/ (m$^2$×atm×24h))</th>
<th>Moisture Permeability / (g/(m$^2$×atm×24h))</th>
<th>Plating Thickness/(nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean Value</td>
<td>SD</td>
<td>CV%</td>
</tr>
<tr>
<td>30</td>
<td>7.96</td>
<td>0.41</td>
<td>5.1</td>
</tr>
<tr>
<td>40</td>
<td>2.10</td>
<td>0.16</td>
<td>7.4</td>
</tr>
<tr>
<td>50</td>
<td>2.04</td>
<td>0.067</td>
<td>3.3</td>
</tr>
<tr>
<td>60</td>
<td>2.48</td>
<td>0.094</td>
<td>3.8</td>
</tr>
<tr>
<td>70</td>
<td>2.35</td>
<td>0.14</td>
<td>5.9</td>
</tr>
</tbody>
</table>

Table 4 presents variations in coating time, oxygen permeability, moisture permeability, and coating thickness of the Al film. The scientific validity and accuracy of the experimental data significantly impact the quality of the Al film. The experimental data were derived from a range of testing equipment. Specifically, measurements for coating thickness SD, CV, and n were acquired using the FTS-S3 C step meter and S4800 cold field emission scanning electron microscope. Optimal conditions for Al coating on the paper substrate were achieved when the coating time was 40 min and the Al coating thickness was below 82 nm.

### 4.4.2. Effect of Coating Time on the Thickness of Al Film on Paper Substrate

Figure 8 presents the curve delineating the relationship between coating time and coating thickness. The figure displays a distinct linear correlation between film thickness and coating time, indicating that film thickness can be readily controlled as a manageable variable in the experiment. The coating thickness evidently increases proportionally with the extension of the coating time. The film’s growth progresses steadily and maintains a near-uniform pattern throughout the continuous discharge period. Furthermore, to ensure a robust linear relationship between film thickness and coating time, estimating the experimental and measurement errors is essential.
For instance, taking into account the limitation on the temperature of the paper substrate, the duration of the substrate passing through the discharge area is kept brief. In response, a higher winding speed is employed to avert abrupt temperature elevation of the substrate. As a result, while the deposition time remains constant, the winding speed is elevated. Despite the accelerated pace and reduced deposition time, the substantial frequency of depositions per unit time aligns with the observation that the deposition rate remains unaffected by the winding speed.

4.4.3. Effect of Coating Time on the Isolation of Paper-Based Al Film

The relationship underscores that, as coating time extends, the aluminized film becomes thicker, and there exists a linear proportionality between coating time and Al coating thickness. At the critical point of 40 min, the film thickness reaches 82 nm. Nonetheless, plating film time exerts a limited influence on the oxygen permeability and moisture permeability of the aluminized film. Hence, a thicker Al coating does not unequivocally yield superior barrier properties.

As depicted in Figure 9, at the 30 min mark, the oxygen and moisture permeability of the aluminized film display a gradual trend. With increased coating time, both oxygen and moisture permeability decrease initially. At 40 min coating time, the barrier performance is optimal. The oxygen permeability is nearly 15 times lower than that of the original film, measuring at 2.04 cm$^3$/(m$^2$ × atm × 24 h), while the water vapor permeability is eight times lower, registering at 0.47 g/(m$^2$ × atm × 24 h). Subsequently, within the 50 min to 60 min interval, the rates of oxygen and water vapor transmission increase.

The formation process of Al film on the paper substrate follows an island growth mechanism. During the initial stages, when the film is extremely thin, its continuity is
disrupted due to the paper’s rough surface. A continuous film can only emerge after the concave sections of the substrate’s surface are filled. The experiment highlights that as coating time extends, the film continuity improves progressively alongside increased thickness. This bolsters the barrier properties of the Al film.

However, beyond a thickness of 82 nm, the oxygen and water vapor permeability of the film cease to decrease with further thickness increases. Oxygen and water vapor penetration primarily occurs through cracks, minuscule pinholes, and other film defects. At this critical thickness, the barrier performance reaches its zenith. Any further increase in Al coating thickness results in heightened film brittleness and exacerbated defect deterioration. Consequently, oxygen and water vapor transmittance through the Al film increases. It is imperative to recognize that blindly extending coating time to augment film thickness can lead to adverse outcomes. Instead, one must heed the critical thickness threshold and explore alternative methods to further enhance the barrier properties of the aluminized film.

4.4.4. Effect of Coating Time on the Structure of Al Film on Paper Substrate

In Figure 10, the surface morphology of the Al films for varying deposition times is exhibited. Initially, as deposition time increases, the Al film demonstrates a tendency towards densification. However, as the coating time continues to extend, a notable increase in Al particles is observed, accompanied by the emergence of stress-induced cracks with heightened film thickness. This development adversely affects the properties of the films, resulting in a decrease in overall quality. Consequently, it can be inferred that the gas barrier properties of the film are enhanced when the surface of the paper-based Al film exhibits greater uniformity.

Surface cracks on the paper-based Al film reduce its ability to resist fluid infiltration, which leads to the infiltration of water vapor into the natural plant cellulose in the paper to form a water bridge, resulting in decreased paper strength. Therefore, the crack phenomenon should be avoided when producing films.

4.4.5. Preparation Results of Paper-Based Al Film and Preparation of Al-Coated Corrugated Paperboard

A high-strength specialty paper was selected as the substrate, and various paper-based Al films were prepared using DC magnetron sputtering, as shown in Figure 11.
Good composite degree uniform texture

Figure 11. Paper-based Al films prepared by DC magnetron sputtering.

By means of the DC magnetron sputtering Al film process, a significant achievement has been realized in producing paper-based Al film. This innovative approach employs high-strength specialty paper as the substrate and utilizes DC magnetron sputtering to create the required Al film, thereby paving the way for the production of aluminum-coated corrugated paperboard. This novel technique contributes to a remarkable enhancement in the surface strength and folding resistance in comparison with the original high-strength specialty paper. Furthermore, the physical properties of the film are substantially improved.

The resultant paper-based Al film exhibits a soft, clear, and delicate surface texture, characterized by a uniform coating. Notably, this transformation also alters the color dynamics. The once vibrant hue of the base paper undergoes a transformation, presenting an array of shades including silver gray, light brown, and light gray. The enhanced color palette ensures improved observability and provides a conducive backdrop for the creation of aluminized corrugated cardboard and the fabrication of innovative furniture designs.

In the context of corrugated paperboard, which consists of surface paper, inner paper, and corrugated core paper bonded together through adhesives to form multi-layer paperboard, the preparation of Al-coated corrugated cardboard hinges on utilizing the developed paper-based Al-coated film as the surface paper. This process adheres to established principles of corrugated cardboard production, leveraging existing equipment and technical workflows. Depending on the specific application requirements, diverse specifications of high-quality Al-plated corrugated cardboard can be manufactured to serve as raw materials for creative furniture, packaging solutions, and cultural and artistic products.

5. Application Design of Al-Plated Corrugated Board

Al-plated corrugated board comprises Al-plated surface paper, inner paper, medium paper, and corrugated paper. Typically, an increased number of layers corresponds to heightened strength. Based on the experimental findings, Al-plated corrugated cardboard exhibits substantial enhancements in various aspects such as water absorption, folding resistance, surface strength, and bursting strength when compared with traditional corrugated cardboard.

Al-plated corrugated board boasts several advantageous attributes, including affordability, versatile utility, fire resistance, moisture resistance, non-toxicity, lack of odor, recyclability, and a contribution to conserving wood resources. As an emerging material, it finds optimal application in the realms of creative furniture, packaging materials, cultural and artistic products, decorations, and other design-driven applications.

5.1. Creative Furniture Application Design

Aluminized film corrugated board offers a versatile canvas for a myriad of creative furniture applications and developments. Products designed with this material not only exhibit a sense of fashion and aesthetics but also prioritize usability. Tailored to the specific design concepts and unique characteristics of furniture pieces, the visual aesthetics can be meticulously crafted, and the corresponding production processes can be seamlessly established. Therefore, the structural design of aluminized film corrugated board assumes particular significance due to its inherent material attributes. It not only dictates
choices in appearance and the appropriate molding procedures but also governs the actualization of product functionalities [16–18].

Irrespective of the specific structural configuration adopted in Al-plated corrugated board furniture, each design encompasses elements of shape and visual design, involving drawing and mold design, as well as assembly considerations. The realm of furniture design is brought to life through ingenious folding, stacking, insertion, and combination techniques. With respect to Al-plated corrugated board furniture, the production process entails intricate sizing design and meticulous attention to load-bearing and stability factors. Depending on the diverse design requisites of the furniture pieces, varying thicknesses of aluminized film corrugated board are chosen. Subsequently, the structural composition and molding processes are judiciously determined, ensuring they align harmoniously with the intended shapes while satisfying load-bearing and stability prerequisites [19–21].

Small and medium-sized furniture pieces, such as stools, tables, and others, often feature folded structures. For instance, a three-layer Al-plated corrugated board can be utilized for die-cutting, indentation, folding, bonding, and combination, along with surface treatment processes, to yield well-formed furniture. This approach harnesses the inherent toughness and rigidity of the material to achieve both robust load-bearing capabilities and structural elegance, as illustrated in Figure 12. In the case of an Al-plated corrugated board with a folding structure, like a multi-seat bench, a straightforward design is tailored to its physical attributes. Design voids within the sheet’s unfolded illustration are aligned with die-cut sections, while indentation lines are introduced at the fold points of the expanded drawing. The expanded Al plated corrugated board is then skillfully folded according to standards, culminating in the formation of a versatile, multi-faceted stool.

Figure 12. Al-plated corrugated board folding structure multi-sided seat stool.

Larger furniture pieces, on the other hand, commonly adopt a plug-in structure, exemplified by storage cabinets and similar items. The primary framework, partitions, and other components of such furniture must meet rigorous strength criteria. This necessitates the utilization of multi-layer composite aluminized film corrugated paperboard materials. Through plate sloting or drilling, these materials are assembled with inserts between the plates. This approach ensures the furniture’s structural integrity and stability while imparting the added visual appeal of graceful curves, as depicted in Figure 13, showcasing an Al-plated corrugated cardboard plug-in structure bookcase. Depending on the designated scheme and design requisites, seven layers of composite Al-plated corrugated cardboard are selected as the base material, with processing techniques determined by the design’s contours. Following standard indentation and die-cutting procedures, the bookcase components are joined through a plug-in combination. For enhanced aesthetics, the exposed edges require edge-sealing treatment.
5.2. Application Design of Cultural Creative Products

The essence of cultural and creative products lies in their cultural and artistic significance, as well as their uniqueness. When Al-plated corrugated cardboard undergoes silicon plating, it gains enhanced gloss and material stability. Its color, typically silver-gray or gray, complements the distinct surface texture of high-strength specialty paper, imparting a notable decorative element. Harnessing the inherent properties of Al-plated corrugated board, this material serves as a foundational resource for the development of cultural and creative products. The process involves crafting innovative design concepts that align with the overarching theme, followed by structural considerations rooted in appearance modeling. Subsequently, a suitable thickness of Al-plated corrugated board is chosen for graphic design, culminating in the creation of molds and installation processes, as depicted in Figure 14, which shows examples of cultural and creative products fashioned from Al-plated corrugated board. An illustration of this concept is the utilization of folding or plug-in structures to craft handicrafts such as architectural or aviation models [22]. Alternatively, a layered or plug-in approach can be adopted to create engaging toys for children of specific age groups, including maritime or weapon models [23]. This strategic application of Al-plated corrugated board demonstrates its versatility in accommodating various forms and functionalities, catering to diverse creative pursuits.

Figure 13. Al-plated corrugated cardboard plug-in structure bookcase.

Figure 14. Al-plated corrugated board cultural creative products.

Corrugated cardboard finds wide-ranging applications in packaging. The Al corrugated cardboard packaging box not only retains the conventional advantages of traditional corrugated cardboard packaging—such as its lightweight nature, cost-effectiveness, and recyclability—but also boasts enhanced waterproof and moisture-resistant properties. This makes it particularly suitable for diverse packaging solutions, ranging from safeguarding against pollution to protecting against corrosion during storage and transportation. Furthermore, by incorporating additional auxiliary materials or employing modular conceptual design, it can be seamlessly integrated into the application design of various other products, thereby expanding its versatility and potential uses [24].
6. Conclusions

Embracing the principles of green design, clean production, resource conservation, and product diversification, this study investigated the critical process parameters of vacuum magnetron sputtering through an orthogonal experiment. The aim was to determine the primary factors impacting the preparation of Al coating. Specifically, the investigation centered around the effects of target–substrate distance, working pressure, and current intensity on the deposition rate of Al coating onto paper.

The ultimate objective was to attain a top-tier aluminized film, setting the stage for the creation of aluminized film corrugated board. Considering the distinctive attributes of Al-plated corrugated board, its potential as a novel furniture material was explored. Additionally, innovative avenues for applying this material in the realms of cultural and creative products and packaging materials were discussed.

The findings presented herein offer valuable insights into meeting the evolving demands of societal consumption and fostering substantial economic benefits for associated enterprises.

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