Article

Magnetron Sputtering Construction of Nano-Al Metallized Wood and Its Functional Research

Yanan Wang, Chengzhu Jin, Xinyi Wang, Qiushuang Li, Wenxuan Li, Qiang Xu and Jingkui Li *

College of Science, Northeast Forestry University, Harbin 150040, China; wang_ya_nan@nefu.edu.cn (Y.W.); 2020214639@nefu.edu.cn (C.J.); 891113822@nefu.edu.cn (X.W.); liqiushuang123@nefu.edu.cn (Q.L.); liwenxuan2020212522@nefu.edu.cn (W.L.); nefu_xq@nefu.edu.cn (Q.X.)
* Correspondence: li_jing_kui@nefu.edu.cn

Abstract: The magnetron sputtering method was used to deposit nano-Al film on the wood surface of Pinus sylvestris L. var. mongholic a Litv., and the material structure, electrical conductivity, mechanical properties and wetting properties were tested and characterized. When the sputtering time was 60 min, the average cross-grain sheet resistance of metallized wood was 695.9 mΩ, and the average along-grain sheet resistance was 227.2 mΩ. Load displacement decreased by more than 88%, elastic modulus increased by 49.2 times, hardness increased by 46 times and surface hydrophobic angle was close to 130°. The grain size of the Al film on the wood surface was presented as nanoparticles, and the arrangement was uniform and dense. The results indicate that without any burden on the environment, the use of magnetron sputtering can quickly and efficiently achieve Al metallization on wood surfaces, so that the wood surface can obtain conductivity and hydrophobic properties. The elastic modulus and hardness of the wood surface were improved, the mechanical properties of the wood were effectively improved and the functional improvement of the wood was realized. This study provides a feasible method and basis for the study of the simple, efficient and pollution-free modification of wood.

Keywords: magnetron sputtering; nano-Al; metallized wood; functionality

1. Introduction

Wood is considered a natural composite material with a hierarchical structure, in which cellulose, hemicelluloses and lignin form a cellular microstructure [1,2]. Wood has the characteristics of light weight, large strength-to-weight ratio, and complex structure [3]. In recent years, due to the deterioration of the environment and the increasingly serious shortage of resources, wood has obtained a broader application prospect [4], showing excellent materials and environmental properties. However, due to wood’s macrostructure, microscopic cell wall structure and ultramicroscopic wall structure, components are vulnerable to damage and erosion, resulting in wood cracking and decay. A large number of wood-based composite materials have been widely used as a substitute for solid wood in outdoor applications, including railings, fences, decks, and door and window frames [5,6]. In recent years, many scholars have made many attempts to improve the performance of wood materials, such as preparing coatings to change the hydrophilic properties of wood and realize the durable and super-hydrophobic properties of wood [7]. As examples, a transparent TiO2/Ce xerogel was formed by chemical methods to provide efficient UV protection for wood [8], and thermal modification technology was used to change the chemical properties of wood to improve the wood’s toughness [9]. Unfortunately, thermal modification technologies at 180–260 °C decrease the hardness, strength and toughness (impact bending strength) of wood, while only the modulus of elasticity of wood can partly be increased by milder thermal modification technologies (lower temperature; shorter time). The preparation processes of many currently used methods are cumbersome and complicated, and many solutions or modifiers are harmful to the human body and the
environment. Therefore, a major challenge is put forward to find pollution-free modification methods and reagents. At present, industry and academia are also encouraging the development of new environmentally friendly woods and other inorganic/organic composite materials [10].

Wood-based inorganic metal nanocomposites are based on wood and artificially combined with one or several metals or alloys to form wood-based composites. The natural conduit in wood can not only serve as a carrier for functional materials, but also provide a path for the transmission of metal ions, which can directly enhance the performance of wood in all aspects. Therefore, the combination of metal and wood can make full use of the excellent properties of each material, eliminate their own inherent defects, and give the composite material new properties [11]. When the particle size of the metal or alloy reaches the nanometer level it will have excellent properties, including high strength, good dimensional stability, wear resistance, aging resistance, and high thermal conductivity [12–14]. Qi Zhang et al. deposited Ni-Fe-P ternary alloy on bamboo by electroless plating, so that the coating penetrated the inner layer of bamboo. The deposition of alloy coating can not only endow bamboo with good electrical conductivity and magnetism, but also greatly improve the thermal stability of bamboo [15]. XieXuqin and other researchers used electroless plating to improve the electromagnetic shielding performance and corrosion resistance of the white parasol wood veneer [16].

In recent years, the application of magnetron sputtering technology in wood-based composite materials has become increasingly extensive [17,18]. Quanliang Wang et al. (2019) reported that natural fiber products with high electromagnetic interference shielding effects were obtained by magnetron sputtering. [19]. C. Nouveau et al. studied the influence of magnetron sputtering coating process parameters on the wear resistance of the coating during the preparation of oriented strand board [20]. Quanliang Wang et al. developed a new type of sandwich structure natural fiber composite material using a magnetron sputtering method [21]. Magnetron sputtering can sputter a thin film with good uniformity and purity on a large area, and can more accurately control the thickness, uniformity and purity of the deposited layer. It also has many advantages, including high adhesion and high deposition rate [22,23]. The magnetron sputtering deposition of metal materials can improve the electrical conductivity, hydrophobicity, mechanical properties and electromagnetic shielding properties of biomass materials, thereby expanding their potential application fields [18,24]. Compared with other methods (e.g., electroless plating, chemical reduction), magnetron sputtering is an ideal technology for the surface modification of natural biomass.

Due to the deterioration of the environment and the increasingly serious shortage of resources, the application prospects of wood will become broader [2]. The “green” modification of wood is imperative and has important strategic significance for realizing the sustainable development of resources. This study is based on the use of magnetron sputtering to construct nano-Al metallized wood to realize the physical properties of electrical conductivity and hydrophobicity that the wood does not have, and to greatly improve the mechanical properties of the wood surface. This research provides a feasible method for realizing environmentally friendly wood modification.

2. Materials and Methods
2.1. Materials

The wood used in the experiment was the sapwood part of Pinus sylvestris L. var. mongholica Litv., which was taken from Hulunbuir, Inner Mongolia. The moisture content of wood after steam drying was 9%. The wood used in the experiment was carefully selected and had no induration, scars or decay. After sanding with 600 mesh, 800 mesh, 1200 mesh, 1400 mesh and 2000 mesh sandpaper, the slice size was 2.5 cm(L) × 2.5 cm(R) × 2 mm(T). Other materials: Al target with 99.99% purity (General Research Institute for Nonferrous Metals, Beijing, China).
2.2. Magnetron Sputtering Construction of Nano-Al Metallized Wood

The sample preparation process used a JGP450 multitarget magnetron sputtering apparatus, the substrate was the treated wood veneer, and a DC (direct current) target was used for the coating process. First, the Al target (purity was 99.99%) was replaced and then the mechanical pump was turned on to draw a low vacuum. When the vacuum degree was lower than 1.0 Pa, the molecular pump was turned on and we started pumping a high vacuum. The sputtering coating experiment was started when the vacuum degree reached \(5.0 \times 10^{-4}\) Pa. Next, we reduced the gate valve (G), adjusted the argon (Ar) flow of the flow meter to 20 sccm and the sputtering pressure to 2.5 Pa, and slowly adjusted the sputtering power to 68 W. When the base temperature was normal, we set the sputtering time to 20 s, 50 s, 15 min, 60 min. The schematic diagram of the construction of nano-Al metallized wood by magnetron sputtering is shown in Figure 1.

\[\text{Ar}^+ \rightarrow \text{Al} \rightarrow \text{substrate} \]

![Schematic diagram of nano-Al metallized wood constructed by magnetron sputtering](image)

**Figure 1.** Schematic diagram of nano-Al metallized wood constructed by magnetron sputtering (“N” and “S” are magnetic poles, “+” is the anode and “−” is the cathode).

2.3. Characterization of Structure and Morphology of Nano-Al Metallized Wood

In this study, an iS10 Fourier transform infrared (FTIR) spectrometer from Thermo Fisher Scientific of the United States was used to analyze the changes in surface functional groups of nano-Al metallized wood. The scanning range was 500–4000 cm\(^{-1}\), the resolution was 4 cm\(^{-1}\) and sampling occurred 32 times. The DXM1200F fluorescence microscope produced by Nikon Corporation of Japan was used to characterize the surface fluorescence effect of nano-Al metallized wood, with a detection magnification of 200. The microscopic morphology of the sample was characterized by a JSM-7500F scanning electron microscope. The structure of nano-Al metallized wood was characterized by X-ray diffraction (XRD-6100, Shimadzu Corporation of Japan, Kyoto, Japan). The test conditions of the X-ray diffractometer were tube pressure of 40 kV, tube flow of 30 mA, scanning range of 5° to 85°, sample fixed tilt angle of 4°, step size of 0.02 and scanning speed of 4°/min.

2.4. Physical Performance Test of Nano-Al Metallized Wood

In this study, a DSA-100S contact angle measuring instrument (Kruss, Hamburg, Germany) was used to measure the water contact angle of the samples. Three different areas were randomly selected from the sample surface, with three positions tested in each area. The test was carried out immediately following the release of the water drops, with the key statistic being the average of the nine tests. Anano-indenter (Nano Indenter G200, Agilent Technologies, Palo Alto, CA, USA) was used to test nano-Al metallized wood, and its Rockwell hardness and Young’s modulus were analyzed. A square resistance tester (DXM1200F, Changzhou Haierpa Electronic Technology Co., Ltd., Changzhou, China) was used to test the conductivity of nano-Al metallized wood.
3. Results and Analysis

3.1. The Structure of Nano-Al Metallized Wood

The XRD pattern of nano-Al metallized wood is shown in Figure 2. After Al nano-film sputtering on the wood surface, the cellulose diffraction peaks 101 and 102 of the wood were always present, indicating that sputtering Al nanoparticles on the wood surface did not alter the primary structure of the wood. When the sputtering time was 20 s, there was little effect on the reduction of the cellulose diffraction peak intensity due to the small number of Al nanoparticles sputtered. However, with increasing sputtering time, the diffraction peaks of crystal cellulose in wood decreased. When the sputtering time was 60 min, the drop in intensity was 25.84%. One reason for the decrease in the intensity of the diffraction peak of wood cellulose is the deposition of an Al film on the surface of the wood, which caused the penetration depth of X-ray radiation to decrease. Another reason is that the deposited Al film absorbed and reflected the diffraction lines, which also caused the intensity of the cellulose diffraction intensity peak to decrease [25]. Moreover, when the sputtering time was 60 min (curve b), the characteristic peak of Al appeared at about 38.8°, indicating that the nano-Al film sputtered well on the surface of the wood, and the nano-Al metallized wood had the common structural characteristics of wood and metal Al.

![Figure 2. XRD patterns of nano-Al metallized wood. (a) Sputtering Al 20 s, (b) Sputtering Al 60 min.](image)

3.2. Nanometer Al Metallized Wood Fluorescence Effect

The fluorescence image of the nano-Al metallized wood surface is shown in Figure 3. Wood fluoresces under ultraviolet light. When the sputtering time was 20 s, there were fewer Al particles sputtered on the surface of the wood, so there was almost no difference in the shape and color from the original wood. When the sputtering time was 50 s, the color of the sample surface began to darken, but the Al particles still did not form a continuous film, and the fluorescence of the wood was not completely covered. From the perspective of the fluorescent emission, as the sputtering time increased, the deposition of Al particles on the surface became more evenly distributed on the surface of the sample. When the sputtering time was 15 min, the surface of the sample began to roughen and almost no fluorescence was emitted. This was the fluorescence surface morphology that appeared after the Al particles aggregated. When the sputtering time was 60 min, the surface of the sample had the same structure as the Al target; the surface of the wood was completely covered and the film was regular and neat.

![Figure 3. Fluorescence image of the nano-Al metallized wood surface.](image)
3.3. Load–Displacement Curve of Nano-Al Metallized Wood

The load–displacement curve of Al metallized wood is shown in Figure 4. The process was divided into three stages: loading, holding and unloading. Compared with the original wood, the load–displacement curve of nano-Al metallized wood is shifted to the left. The sample with a sputtering time of 20 s had a lower deviation than the one with a sputtering time of 60 min. From the loading curve, the loading displacement of the original wood was 1177 nm; at a sample coating time of 20 s, the loading displacement was 646 nm. The sample with a coating time of 60 min had a loading displacement of 133 nm, a drop of almost 89% relative to the original wood. For the holding stage, the holding displacement of the original wood was the largest, while that of the metallized wood with a sputtering time of 60 min was the smallest. The deposition of Al film on the surface of the wood veneer caused both the load displacement and retention displacement to decrease.

3.4. Nano-Al Metallized Wood Hardness and Elastic Modulus

The hardness and elastic modulus of nano-Al metallized wood are shown in Figure 5. The elastic modulus and hardness values of each group represent the average of 14 groups of values. The elastic modulus of the original wood was 0.267 GPa and the hardness was 0.032 GPa; for a sputtering time of 20 s, the elastic modulus of the Al metallized wood was 1.192 GPa and the hardness was 0.052 GPa; the elastic modulus increased 3.46 times, and
the hardness increased 0.63 times. As there were fewer Al particles on the surface of the sample after the sputtering time of 20 s, there was almost no difference in the unloading displacement with the original wood. When the sputtering time was 60 min, the elastic modulus of Al metallized wood was 13.4 GPa and the hardness was 1.504 GPa; the elastic modulus increased by 49.2 times and the hardness increased by 46 times. As the sputtering time increased, Al nano particles continued to increase, filling the voids in the wood and forming a continuous Al film. Since the elastic modulus and hardness of metal Al are much higher than that of wood, the deposition of Al film on the surface of the wood veneer rapidly increased the elastic modulus and hardness of the wood veneer, improving the mechanical properties of the wood surface.

![Figure 5. Hardness and elastic modulus of metallized wood.](image)

### 3.5. Electrical Conductivity of Nano-Al Metallized Wood

The sheet resistance of nano-Al metallized wood is shown in Table 1. No sheet resistance was detected on the sample surface for original wood, after 20 s Al film sputtering, or after 50 s. This was due to the short sputtering time and the fewer Al particles sputtered, and because the distribution of Al particles was still very loose, with no island-like structure formed. When the sputtering time was 15 min, the average cross-grain sheet resistance of the sample was 326.43 mΩ, and the average along-grain sheet resistance was 138.33 mΩ. At this point, the Al nanoparticles on the surface of the sample were connected into flakes to form a dense film, indicating that an Al film with conductive properties can be quickly prepared on the surface of the wood. When the sputtering time was 60 min, the average cross-grain sheet resistance of the sample surface reached 695.9 mΩ, 2.1 times that of the sample sputtered for 15 min, while the average along-grain sheet resistance reached 227.2 mΩ. The surface flatness and uniformity of the nano-Al metallized wood were also superior.

| Sample Name | Cross-Grain Sheet Resistance (mΩ) | Along-Grain Sheet Resistance (mΩ) | Average Cross-Grain Sheet Resistance (mΩ) | Average Along-Grain Sheet Resistance (mΩ) |
|-------------|----------------------------------|----------------------------------|------------------------------------------|------------------------------------------|
| The original wood | - | - | - | - |
| (Al) 20 s | - | - | - | - |
| (Al) 50 s | - | - | - | - |
| (Al) 15 min | 316.70 | 328.10 | 334.50 | 141.90 | 135.80 | 137.30 | 326.43 | 138.33 |
| (Al) 60 min | 697.20 | 682.00 | 708.70 | 226.60 | 220.70 | 234.30 | 695.9 | 227.2 |

“-” means no value or no value detected.
3.6. Hydrophobic Effect of Metallized Wood

The hydrophobic effect of nano-Al metallized wood is shown in Figure 6. The contact angle of the original wood surface was 63°, indicating a hydrophilic surface. When the Al film was sputtered for 20 s, the contact angle was 110.9°, and the wettability of the wood surface changed from hydrophilic to hydrophobic. As the sputtering time increased, the contact angle of the veneer surface gradually increased. When sputtered for 50 s, the contact angle was 119.5°; the film on the surface of the veneer formed an island-like structure but did not completely cover the microstructure of the veneer surface. For sputtering times of 15 min and 60 min, the contact angles were 132.7° and 129.9°, respectively. Compared with sputtering for 15 min, the change was minimal, indicating that when a uniform film is formed on the surface of the wood veneer, the wettability of the sample surface tends to be stable, and that the thickness of the continuous nano-Al film on the wood surface is not a dominant factor for its wettability. The Al film deposited on the surface of the wood improved the porous structure of the wood, with a large number of hydrophilic polar functional groups on the surface covered by the Al film, which improved the hydrophobicity of the wood.

![Figure 6. Hydrophobic diagram of metallized Pinus sylvestris wood veneer](image)

3.7. Micro Morphology of Metallized Wood

The scanning electron micrograph of nano-Al metallized wood is shown in Figure 7. The cellulose distribution can be clearly seen on the surface of the original wood, with the wood having larger tube holes. When the sputtering time was 20 s, the deposition rate was rapid, with the cellulose structure of the wood surface covered under a microscope at 10,000 times. When the sputtering time was 50 s, the structure of Al nanoparticles wrapped around the wood surface was visible. The original structure of the wood could not be seen under the microscope; most of the pores between the fibers were filled with Al atoms and the surface of the sample became smooth. When the sputtering time was 15 min, the wood surface was completely covered by a uniform and continuous Al nano-film. When the sputtering time was 60 min, the surface of the metallized wood was clearer and smoother; the Al film had no cracking or agglomeration and the arrangement was uniform and dense. The surface pores between the fibers on the surface of the sample formed a micron-scale rough structure, while the Al atoms deposited on the surface of the fiber formed a nanostructure similar to Al film [19].
Figure 7. SEM image of nano-Al metallized wood ((a) the original wood, (b) sputtering Al 20 s, (c) sputtering Al 50 s, (d) sputtering Al 15 min, (e) sputtering Al 60 min).

3.8. Fourier Transform Infrared Spectroscopy Analysis

The infrared spectroscopy (FTIR) analysis of nano-Al metallized wood is shown in Figure 8. In the original wood, the characteristic peak at 3333 cm$^{-1}$ was O-H stretching vibration. As the sputtering time increased, when the sputtering time was 15 min, this characteristic peak was completely covered by Al nanoparticles. With increased sputtering time, the characteristic peak intensity of the C-O stretching vibration of wood at 1060 cm$^{-1}$ gradually decreased, and the sample surface was completely covered by Al nanoparticles. The Fourier transform infrared spectrum of nano-Al metallized wood showed that the functional groups on the wood surface were effectively covered by the deposited film, with a continuous film formed on the wood surface after 15 min of sputtering.

Figure 8. Infrared spectrum (FTIR) of nano-Al metallized wood.
4. Conclusions

During the process of depositing nano-Al film on the surface of wood by magnetron sputtering, Al nanoparticles could be effectively combined with the wood veneer to form a uniform and continuous film and realize the metallization of the wood surface. When the sputtering time was 60 min, the average cross-grain sheet resistance of metallized wood was 695.9 mΩ and the average along-grain sheet resistance was 227.2 mΩ. The load displacement decreased by more than 88%, the elastic modulus increased by 49.2 times, the hardness increased by 46 times and the surface hydrophobic angle was close to 130°. The particle size of the Al film was presented as nanoparticles, and the arrangement was uniform and dense. The results suggest that, without any burden on the environment, the use of magnetron sputtering can quickly and efficiently achieve Al metallization on wood surfaces. The Al metallization of the wood surface conferred conductive and hydrophobic properties upon the wood surface, and improved the elastic modulus and hardness of the wood surface, effectively improving the mechanical properties of the wood and realizing its functional improvement. The use of magnetron sputtering to quickly and efficiently realize the surface metallization of wood veneers is currently only at the laboratory stage, and large-scale industrial promotion still has some difficulties. However, it has important practical significance to obtain static shielding wood-based materials, antistatic wood-based composite materials and far-infrared wood-based functional materials.

Author Contributions: Conceptualization, Y.W. and J.L.; methodology, Y.W.; experimental part, Y.W., C.J. and J.L.; formal analysis, Q.X.; investigation, X.W.; data analysis, Q.L.; search literature, W.L.; writing—original draft preparation, Y.W.; writing—review and editing, J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Central Universities and grant number is 2572020BC08, and funded by Innovation Training program for college students of Northeast Forestry University and grant number is 202110225085.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Mark, J.E.; Calvert, P.D. Hybrid and in situ composites. Mater. Sci. Eng. C 1994, 1, 159–170. [CrossRef]
2. Greil, P.; Lifka, T.; Kaindl, A. Biomorphic cellular silicon carbide ceramics from wood: II. mechanical properties. J. Eur. Ceram. Soc. 1998, 18, 1975–1983. [CrossRef]
3. Sun, J.A.; Yang, Y.S.; Dang, B.K.; Chen, Y.P.; Wang, Y.Y.; Zhang, J.Y.; Qiu, J. Research progress of the preparation of biomimetic superhydrophobic wood surface micro-nano structures. J. For. Eng. 2021, 6, 1–11. [CrossRef]
4. Wang, Z.Y.; Qu, L.J.; Qian, J.; He, Z.B.; Yi, S.L. Effects of the ultrasound-assisted pretreatments using borax and sodium hydroxide on the physicochemical properties of Chinese fir. Ultrason. Sonochem. 2018, 50, 200–207. [CrossRef]
5. Wang, Q.W.; Yi, X.; Shen, J. Tailoring wood-plastic composites for furniture production: Possibilities and opportunities. J. For. Eng. 2016, 1, 1–8. [CrossRef]
6. Félix, J.S.; Domeño, C.; Nerin, C. Characterization of wood plastic composites made from landfill-derived plastic and sawdust: Volatile compounds and olfactometric analysis. Waste Manag. 2013, 33, 10–15. [CrossRef] [PubMed]
7. Shah, S.M.; Zulfiqar, U.; Hussain, S.Z.; Ahmad, I.; Habib, U.R.; Hussain, I.; Subhani, T. A durable superhydrophobic coating for the protection of wood materials. Mater. Lett. 2017, 203, 17–20. [CrossRef]
8. Guo, H.Z.; Klose, D.; Hou, Y.H.; Jeschke, G.; Burgert, I. Highly Efficient UV Protection of the Biomaterial Wood by a Transparent TiO2/Ce Xerogel. ACS Appl. Mater. Interfaces 2017, 9, 39040–39047. [CrossRef]
9. Gaff, M.; Kacik, F.; Gasparik, M. Impact of thermal modification on the chemical changes and impact bending strength of European oak and Norway spruce wood. Compos. Struct. 2019, 216, 80–88. [CrossRef]
10. Chaiwutthinan, P.; Chuayjuljit, S.; Srasomsub, S.; Boonmahitthisud, A. Composites of poly(lactic acid)/polybutylene adipate-co-terephthalate) blend with wood fiber and wollastonite: Physical properties, morphology, and biodegradability. J. Appl. Polym. Sci. 2019, 136, 47543. [CrossRef]
11. Chai, Y.; Fu, F.; Liang, X.Q. Progress of wood based metal functional composites. J. Beijing For. Univ. 2019, 41, 151–160. [CrossRef]
12. Klimowicz, T.F. The largescale commercialization of aluminummatrix composites. JOM 1994, 46, 49–53. [CrossRef]
13. Schuster, D.M.; Skibo, M.D.; Bruski, R.S.; Provencher, R.; Riverin, G. The recycling and reclamation of metal-matrix composites. JOM 1993, 45, 26–30. [CrossRef]
14. Lucchetta, G.; Marinello, F.; Bariani, P.F. Aluminum sheet surface roughness correlationwith adhesion in polymer metal hybrid overmolding. CIRP Ann. 2011, 60, 559–562. [CrossRef]
15. Zhang, Q.; Ning, L.P.; Wang, C.Y.; Wang, M.; Shen, Y.Z.; Yan, Y.R. Fabrication and characterization of bio-based shielding material with dissimilar surface resistivity prepared by electroless Ni–Fe–P alloy plating on bamboo (N. affinis). *J. Mater. Sci. Mater. Electron.* **2019**, *30*, 21064–21078. [CrossRef]

16. Xie, X.Q.; Cheng, M.J.; Dai, V.D.; Jia, H.L.; Wang, L.J. Study of Electroless Plating of Ni-Fe Alloy on Triplochiton Sclexylon Veneer. *Furniture* **2019**, *231*, 57–61. [CrossRef]

17. Wang, Y.N.; Wu, X.T.; Wang, Y.B.; Tian, Y.Q.; Mu, H.B.; Li, J.K. Hydrophobic and UV-resistant properties of environmentally friendly nano-ZnO-coated wood. *Holzforschung* **2020**, *75*, 138–147. [CrossRef]

18. Li, J.K.; Wang, Y.N.; Zhao, H.Z.; Qi, D.W. Research on the gradual process of the structure and mechanical properties of NanoZnO-coated veneer. *Wood Sci. Technol.* **2021**, *55*, 243–255. [CrossRef]

19. Wang, Q.L.; Xiao, S.L.; Shi, S.Q.; Xu, S.Y.; Cai, L.P. Self-bonded natural fiber product with high hydrophobic and EMI shielding performance via magnetron sputtering Cu film. *Appl. Surf. Sci.* **2019**, *475*, 947–952. [CrossRef]

20. Nouveau, C.; Djouadi, M.A.; Decès, P.C. The influence of deposition parameters on the wear resistance of CrxNy magnetron sputtering coatings in routing of oriented strand board. *Surf. Coat. Technol.* **2003**, *174*, 455–460. [CrossRef]

21. Wang, Q.L.; Tang, J.; Xiao, S.L.; Wang, M.; Shi, S.Q. Natural fiber-based composites with high hydrophobic, magnetic, and EMI shielding properties via iron oxide in situ synthesis and copper film deposition. *BioResources* **2020**, *15*, 8384–8402. [CrossRef]

22. Sarakinos, K.; Alami, J.; Konstantinidis, S. High power pulsed magnetron sputtering: A review on scientific and engineering state of the art. *Surf. Coat. Technol.* **2010**, *204*, 1661–1684. [CrossRef]

23. Wan, C.; Jiao, Y.; Li, J. A cellulose fibers-supported hierarchical forest-like cuprous oxide/copper array architecture as a flexible and free-standing electrode for symmetric supercapacitors. *J. Mater. Chem. A* **2017**, *5*, 17267–17278. [CrossRef]

24. Alexeeva, O.K.; Fateev, V.N. Application of the magnetron sputtering for nanostructured electrocatalysts synthesis. *Int. J. Hydrogen Energy* **2016**, *41*, 3373–3386. [CrossRef]

25. Xu, Y.; Wang, Z.S.; Xu, J.; Zhang, Z.; Wang, H.C.; Zhu, J.T.; Wang, F.L.; Wang, B.; Qin, S.J.; Chen, L.Y. Characterization of low-Z material layer profiles in bilayer structures by X-ray reflectivity measurement. *Opt. Precis. Eng.* **2007**, *15*, 1838–1843.