High-performance aramid fabric in infrared shielding by magnetron sputtering method

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Abstract

In addition to providing basic protective functions, modern military uniforms are also being designed to provide special functions, such as infrared shielding. In this study, a nanoscale copper film was deposited on Kevlar para-1414 aramid fabric by magnetron sputtering technology to significantly enhance infrared shielding. The deposition of a uniform nano-copper film on the surface of the aramid fabric enhanced infrared shielding, tensile strain, and conductivity, which is of guiding significance for the development of infrared shielding garments.

1. Introduction

Infrared sheathing technology has been a research hotspot for decades due to its promising applications in military uniforms and special garments [1]. This technology can limit the efficacy of infrared detection equipment by decreasing the surface temperature of the material, and is also expected to be applied in clinical care, wearable devices, protective clothing and other fields [2]. Therefore, more efforts are expected to be devoted to developing more efficient and economical fabrication methods to produce high-performance functional textiles.

Rather than film plating on traditional hard objects, future efforts are expected to use a flexible substitute [3, 4]. At present, the main plating methods for soft substrate textile and clothing fabrics include electroless plating, vacuum evaporation and magnetron sputtering [5, 6]. Electroless plating is generally limited in many applications because of its high contamination rates [7]. Vacuum evaporation plating is relatively simple, but it is inefficient and has poor adhesion of the substrate [8]. In contrast, magnetron sputtering technology is a high-tech film deposition process with the advantages of low substrate temperature, stable performance, time-efficiency and zero pollution production [9–12]. By depositing a metal film on the surface of clothing fabric via magnetron sputtering, the fabric can be given special properties, which expands the application scope of clothing. For example, clothing can be given the properties of electromagnetic shielding, antistatic conduction, intelligent sensing, energy production through thin film solar cells, anti-ultraviolet antibacterial, and infrared shielding functions [13–17]. Jiang et al. once prepared copper film deposited nylon yarn by magnetron sputtering at different winding speeds to achieve enhanced electrical conductivity [18]. Zhang et al. used magnetron sputtering to deposit a copper film of different thickness on polyester fabric and studied its electromagnetic shielding performance [19]. Currently, applying magnetron sputtering technology to the textile and clothing field is still in the exploration stages, and is greatly expected to be applied to large-scale industrial production.

In this study, a nano-sized copper metal film was deposited on the surface of aramid fabric by a facile magnetron sputtering method, resulting in a special metalized garment with enhanced infrared shielding functionality. Aramid was selected as the clothing material due to its high-temperature resistance, high strength, and wide application in the military field. This study quantitatively explored the feasibility of sputtering copper
film on an aramid fabric surface with magnetron sputtering technology and demonstrated an enhanced infrared shielding performance.

2. Experimental section

As schematically shown in figure 1, commercial Kevlar was used for the experimental aramid fabrics, and the copper (Cu) target was obtained from ZhongNuo Advanced material. The coating was applied at room temperature (25 °C) with a magnetron sputtering system (Technol, JCP200). Prior to the deposition, the aramid fabrics were ultrasonically cleaned in acetone and ethanol. The deposition parameters are listed in table 1. Sputtering times of 2.5 min, 5 min and 10 min were used to produce aramid fabrics with three different copper layer thicknesses.

The thickness of the copper film deposited onto the fibers was measured by using a Bruker DektakXT surface profiler. The surface morphology of the copper coated aramid fabric was examined by using a scanning electron microscope (SEM) (with NIKON SMZ745T). The crystal structure of the copper coated aramid fabric was characterized by using a θ/2θ X-ray diffractometer (Rigaku Smartlab–advanced) which uses copper Kα radiation (k = 0.15 nm) in the normal mode. The X-ray diffraction (XRD) patterns were investigated at 2θ angles which ranged between 10° and 90° with a scanning increment of 0.1° and scanning speed of 5°/min. The square resistance of the sample fabrics was measured with a HPS2523 digital multimeter at room temperature (20 °C–25 °C) and a relative humidity (RH) of 60–65. The measurements were conducted with 6 checking points (3 points in weft and 3 points in warp) and the mean values were calculated. The tensile properties were tested by using a Instron 5944 single column tensile and compression tester, under the ISO 2062:2009 standard, with a tensile speed of 300 mm/min and a gauge length of 100 mm. A Fluke Ti400 infrared thermal camera was used to capture the infrared images.

![Figure 1. Schematic diagram of magnetron sputtering treating on aramid fabric.](image)

| Table 1. Parameters of magnetron sputtering. |
|---------------------------------------------|
| Material Parameter                          |
|---------------------------------------------|
| Target materials                            |
| Cu (99.99%)                                  |
| Initial vacuum                              |
| 2 × 10⁻⁴ Pa                                  |
| Deposition vacuum                           |
| 0.25 Pa                                      |
| Flow velocity of Argon gas                  |
| 100 sccm                                     |
| Distance between target and substrate       |
| 9 cm                                         |
| Substrate material                          |
| Kevlar Aramid fabrics (10 cm × 10 cm, 1.5 D × 51 mm) |
| Current intensity                           |
| 0.5 A                                        |
| Sputtering time                             |
| 2.5 min, 5 min and 10 min                   |

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First, the copper film thickness for the various sputtering times was determined as shown in table 2. The copper film thickness increased with increased sputtering time and was proportional to the deposition time. Additionally, observation by SEM of the aramid fabric at various times of copper deposition (figures 2(a)–(c)) indicated that the surface of unprocessed aramid fibers was relatively smooth, and the surface roughness of the fabric increased after being sputtered with copper. Additionally, the size of copper nanoparticles increased with extended sputtering time. Specifically, the average particle diameter increased from 18.5 to 32.6 nm when the deposition time increased from 2.5 to 10 min. With increased sputtering time, copper atoms had increased opportunities to collide into each other and form clusters, thereby creating larger particle sizes.

As illustrated in figure 3(a), the diffraction spectrum of uncoated aramid fabric samples showed characteristic peaks of (110), (200) and (211) at 20.3°, 23° and 29° respectively. After copper sputtering, these three characteristic peaks remained constant, indicating that the crystal characteristic peaks of Kevlar aramid fabrics did not change significantly after magnetron sputtering treatment. When the aramid was sputtered with copper, regardless of sputtering time, a copper (111) peak at 42.9° was clearly observed in the spectrum. In addition, it was observed that the peak strength of the copper (111) increased with increased sputtering time, that is, the half-peak full width (FWHM) increased with increased sputtering time. These results showed that the thickness of the deposited copper film was directly proportional to the sputtering time, and the increased film thickness was conducive to the crystallization of the copper film, which was also consistent with the results of morphology analysis.

Table 2. The relationship between different sputtering times and copper film thickness.

| Sputtering time (min) | Thickness (nm) |
|----------------------|----------------|
| 2.5                  | 103            |
| 5                    | 199            |
| 10                   | 404            |
For conductivity performance, the prepared material was evaluated with film block resistance. Here, the square resistance calculation formula was defined as:

\[ R = \frac{\rho}{d} \] (1)

Where, \( R \) was film resistance (\( \Omega \)), \( \rho \) was the specific resistance (\( \Omega \cdot m \)), and \( D \) was the thickness (m). The effect of magnetron sputtering time on the square resistance of copper-coated aramid fabric is shown in Table 3. With a sputtering time of 2.5 min, samples had a mean square resistance of 177.7 m\( \Omega \). This suggests that if the sputtering time is too short, the sedimentary copper nanoparticles on the aramid just broke the discontinuous island structure, and particle size distribution was not uniform, resulting in a poorer membrane surface crystalline state. This caused electron mobility to be low, as thinner surfaces tend to have poorer conductivity. With sputtering times of 5 and 10 min, the mean square resistance of the samples was measured to be 82.2 m\( \Omega \) and 38.7 m\( \Omega \), respectively. Thus, increasing the sputtering time enhanced the conductivity of the samples, due to an increased thickness of the copper coat. These results suggested that both copper film thickness and film conductivity are proportional to sputtering time. Further resistance testing showed that the difference in the warp and weft square resistance of the copper-coated aramid fabric was insignificant, indicating that the aramid surface became relatively flat and smooth after copper sputtering.

Furthermore, Figure 3(b) and Table 4 report the tensile stress and tensile strain of the copper-coated aramid material based on sputtering times. When sputtered with copper for 10 min, the aramid fabric’s tensile stress significantly increased from 464 MPa to 555 MPa. This is because the deposited nano-level copper film strengthened the structure of the yarn, improving the fabric surface strength, and strengthening some weak parts.
of the original fabric. In addition, when sputtered with copper, the tensile strain of the aramid fabric also decreased. As sputtering time increased from 2.5 min to 10 min, the tensile strain of the sample decreased further, with a sputtering time of 10 min resulting in a strain of about 0.151% compared to a strain of 0.175% in the untreated aramid. This is because the rigidity of copper is greater than the aramid, so the rigidity of the material increased when sputtered with copper atoms.

In general, the total energy radiated by an object per unit time is defined by Stephen-Boltzmann’s law as

$$W = \varepsilon\sigma T^4$$

(2)

where $W$ is the total radiation emission, $\sigma$ is the Boltzmann constant, $\varepsilon$ represents the emittance, and $T$ is the absolute temperature. Thus, infrared shielding can be achieved by reducing surface emissivity or target temperature[20].

### Table 4. Stress strain value of each sample.

| Sample                  | Tensile Stress | Tensile Strain |
|-------------------------|----------------|---------------|
| Blank aramid fabric     | 464 MPa        | 0.175%        |
| Sample sputtered for 2.5 min | 512 MPa       | 0.162%        |
| Sample sputtered for 5 min    | 521 MPa       | 0.158%        |
| Sample sputtered for 10 min   | 555 MPa       | 0.151%        |

**Figure 4.** Infrared thermal images of human arm under various conditions: (a) the arm without covering (b) the arm covered by aramid fabric without copper sputtering (c) the arm covered by aramid fabric with copper sputtering for 2.5 min (b) the arm covered by aramid fabric with copper sputtering for 5 min (e) the arm covered by aramid fabric with copper sputtering for 10 min.
It is widely known that the higher the reflectivity of an opaque surface, the lower the absorption rate and the lower the emissivity. The low infrared emissivity mentioned above is a necessary condition for infrared shielding. As the infrared radiation of human body is concentrated in the band of 8–16 μm, improving the reflectance of this wavelength is necessary to achieve infrared shielding, which can be done by introducing a metal film with high infrared reflectance.

Figure 3(c) shows the relationship between the infrared reflectance of the copper-coated aramid fabric in the range of 8–16 μm with respective sputtering times. With increased sputtering times, the infrared reflectance of the sedimentary layer gradually increased due to increased copper film thickness. When the sputtering time was 10 min, the infrared reflectance was the highest, reaching above 0.9. Figure 4 shows a thermal image of a researcher’s arm recorded by the infrared thermography under various conditions: uncovered, covered with the uncoated aramid fabric, and covered by the copper coated aramid fabrics. The uncovered arm had the highest radiation temperature, while the aramid fabric that had been sputtered with copper for 10 min had the lowest radiation temperature. According to Stefan-Boltzmann’s law, the sputtering on copper film on the aramid surface could significantly reduce the infrared emissivity of the fabric [21].

4. Conclusion

In summary, this study demonstrates the feasibility and efficacy of using magnetron sputtering to dispense a copper film on the surface of an aramid fabric to achieve enhanced infrared shielding performance. The modified aramid fabric also exhibited improved tensile strain and conductivity, thus indicating a future application in the military and other fields. More importantly, the demonstration of the fabrication process provides a valuable experimental precedent for the future development of functional garments.

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