Study on fabrication of nano copper by thermal plasma and their applications in thermal camouflage

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ABSTRACT

In this study, we investigated the process of coating mica substrates with a layer of copper (Cu) metal nanoparticles to enhance thermal camouflage by reducing thermal emission. The Cu nanoparticles were fabricated using the Plasma Temperature method, achieving an average size of approximately 100 ÷ 200 nm. The structure, morphology, composition, and properties of Cu nanoparticles were characterized by scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), and Fourier transform infrared (FTIR). The infrared emission characteristics after coating Cu metal nanoparticles on mica substrates were measured by an SR5000N spectrophotometer, an SR800N-7° absolute blackbody, and a Flir Armasight thermal imaging camera. The results indicated that the material samples containing 10% Cu and 50% Cu had noticeably lower emission intensities compared with the other samples, especially in the long-wavelength region. This was applied to the Cu nano-coating work, which reduced the thermal emission of mica. This result demonstrated the ability of the nano-metallic material to modulate the surface emission rate, thereby reducing the detectability of the object by thermal imaging devices for camouflage applications.

Keywords: Thermal camouflage applications; Reduce thermal emission; Coating metal nanoparticles; Nanoparticle Cu.

1. INTRODUCTION

Metallic nanomaterials are pivotal for advancing thermal imaging and camouflage technologies due to their unique optical and thermal properties [1]. For thermal imaging, the surface plasmon resonance (SPR) in nanoparticles such as Au, Ag, and Cu enhances light absorption and scattering, thereby improving sensor sensitivity and resolution [2, 3]. In thermal camouflage, these nanomaterials modulate thermal emissivity often within epsilon-near-zero (ENZ) films to reduce infrared detection, a critical capability for military applications [4, 5]. Furthermore, their integration into advanced systems, such as graphene-based composites or dual-functional platforms, enables adaptive camouflage combined with thermal management for electronics [6].

Among metal nanomaterials, copper (Cu) nanomaterials possess unique photothermal properties, allowing for effective tuning and control of infrared absorption and emission. Cu nanoparticles have strong absorption in the short wavelength range, including the UV region and part of the VIS region, thanks to the localized surface plasmon effect (LSPR) [7]. In the infrared region, Cu nanomaterials tend to absorb less energy than other materials, such as metal oxides. This makes Cu nanomaterials a suitable choice for thermal camouflage applications, limiting the absorption of unwanted infrared energy, making the nanocoated surface less detectable by infrared detectors. A notable feature of Cu nanomaterials is their low infrared emissivity, especially when coated on various surfaces [8]. The low emissivity allows Cu nanocoated materials to reduce the amount of heat emitted, limiting the possibility of being detected in thermal imaging systems. This emission property also depends on the concentration and coating method, as a thick and uniform coating often optimizes the thermal camouflage effect of nano Cu. Nano Cu materials have high thermal stability, which helps maintain their infrared absorption and emission properties in harsh environments [9]. This stability is important for applications that require long-term durability under elevated temperatures, such as in military or outdoor environments. Furthermore, given the chemical properties of copper, nano Cu particles can be protected against oxidation to ensure long-term performance. In addition, by varying the particle size, density, and coating method, the absorption and emission properties of nano Cu can be tuned [10]. Smaller nano Cu particles typically have higher absorption, while denser coatings reduce thermal emission, improving the infrared cloaking ability of the material. Therefore, optimizing the fabrication parameters will allow controlling the photothermal properties of Cu nanocoatings according to the application requirements.

Cu nanomaterials, with their low infrared emissivity and tunable optical–thermal properties, are promising candidates for thermal control and camouflage applications. In this study, Cu nanoparticles were synthesized via the Thermal Plasma method, and their structural and infrared emission characteristics were evaluated after being coated on mica substrates. Although the potential of nano-Cu for thermal camouflage is evident, systematic studies on the effects of parameters such as dispersion time and nanoparticle concentration on the emissivity of Cu nanocoatings on mica remain limited. Therefore, this work investigates how these dispersion parameters affect the thermal emission reduction of Cu nanocoatings for camouflage applications.

2. EXPERIMENTAL

2.1. Selection and preparation of substrate

2.1.1. Criteria for selecting substrate

Selecting the right substrate is crucial for ensuring the effectiveness and durability of the coating. When choosing a substrate, the main criteria to consider include compatibility with the coating material, resistance to environmental factors, high mechanical strength, flexibility to adequately support the coating, and low production costs.

2.1.2. Test sample preparation

The following substrate materials are considered ideal choices for use in small laboratory experiments due to their superior properties: *(i) Mica:* Due to its absolute flatness at the atomic level, chemical inertness, and transparency, mica is an ideal substrate for coating research experiments, ensuring highly accurate and stable results. *(ii) Polyester:* Due to its high mechanical strength, shape retention, and good compatibility with nano-coatings, polyester is an ideal substrate for military and camouflage applications, ensuring long-term stability and multi-spectral concealment effectiveness. *(iii) Polyamit (Nylon):* With its high mechanical strength, abrasion resistance, and good adhesion to nanocoatings, polyamide is an ideal substrate that ensures durability and enhances thermal/infrared camouflage effectiveness under various environmental conditions.

In this study, mica was selected as the primary substrate due to its atomic-level flatness, chemical inertness, and transparency. These characteristics enable an accurate evaluation of the nanocoating's properties without interference from substrate effects. Polyester and polyamide, although promising for their flexibility and mechanical durability, were excluded from the present study. The initial objective was to first establish the fundamental performance on an ideal, well-controlled substrate. These materials will be investigated in future work to assess the applicability of Cu nanocoatings on flexible platforms for practical camouflage systems.

2.2. Method of fabrication of Cu nanoparticles

Cu nanoparticles are manufactured by the Thermal Plasma method of the Institute of Materials Science through the process of vaporizing the input Cu raw material powder (size from a few tens to a few hundreds of μm) to form Cu nano product particles, as shown in figure 1. When the Cu raw material powder is fed into the high-temperature plasma zone (hot zone), the raw material powder is vaporized into atomic molecules immediately. Then the vapor mixture of atomic molecules escapes the plasma zone and enters a much lower temperature zone (quenching zone). At that time, the molecular atoms will aggregate to form metal nanoparticles or nano oxides. Due to the extremely high cooling rate in the reactor, which can be up to $10^5 \div 10^6$ °C/s, the size of the metal nanoparticles or nano oxides achieved gradually increases over time, from a few to a few tens of nanometers.

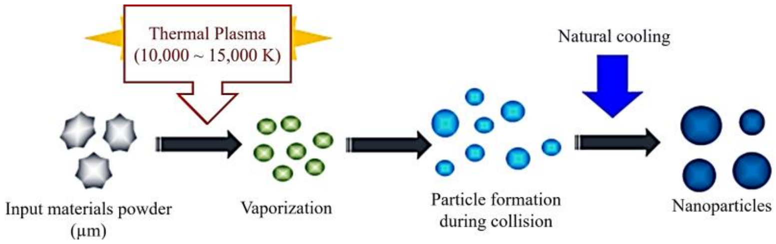


Figure 1. *Process of vaporizing raw material powder and forming Cu nanoparticle production.*

2.3. Coating method and parameter control

2.3.1. Metal nano coating technology

A copper (Cu) nanocoating was fabricated on a 3x3 cm mica substrate using a solution deposition method. A mixture of Cu nanoparticles dispersed in a polyurethane (PU) solvent was heated to 110 °C, then coated onto the substrate to a thickness of 100 μm and dried at room temperature to form a well-adhered film.

2.3.2. Influence of material size, structure and density

The thermal camouflage performance of Cu nanocoatings depends on three key factors: nanoparticle size, coating structure, and particle density. This study focuses on evaluating the performance of coatings fabricated with Cu nanoparticle concentrations of 10 wt.% and 50 wt.% to find the optimal balance between concealment and mechanical properties.

2.3.3. Survey to evaluate infrared emission characteristics

The infrared emission characteristics evaluation system of material samples consists of three main instruments: SR5000N spectroradiometer, SR800N-7A absolute blackbody, and Flir Armasight thermal imaging camera. Details of the instruments are presented in tables 1, 2, and 3 below.

Table 1. *SR5000N spectroradiometer and main technical parameters.*

Main technical parameters:

Spectrum, μm	2.5 ÷ 14.3
Spectral resolution (by wavelength),%	2
Spectrum scanning speed, spectrum/s	≤ 50
Noise performance, mK	5
Field of view, mrad	0.5÷7
Focus range, m	3 ÷ ∞

Table 2. *SR800N-7A absolute blackbody and main technical parameters.*

Main technical parameters:

Blackbody emitter size, inch	7×7
Absolute temperature range, °C	0 ÷ 125
Temperature differential range, °C	- 25 ÷ 100
Uniformity, °C	± 0.01
Setpoint resolution, °C	0.001
Emissivity	0.98 ± 0.02

Table 3. *Flir Armasight thermal imaging camera and main technical parameters.*

Main technical parameters:

Spectrum, µm	8 ÷ 14
Receiver resolution, pixels	336 x 256
Pixel size	17 µm
Thermal sensitivity, mK	< 50
Objective lens type	germanium
Magnification, times	10
Field of view, degree	10.3°
Focus range, m	5 ÷ ∞

In the experiment, material samples are heated to 50 ºC and placed 5 m from the SR5000N spectroradiometer and/or the Flir Armasight camera. These devices record data as a spectrum graph or thermal image, while the SR800N-7A blackbody is used for system calibration (figure 2).

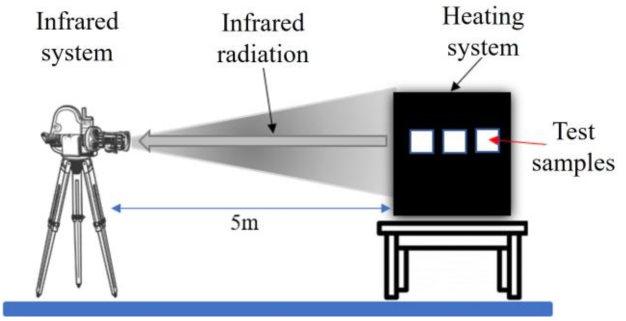
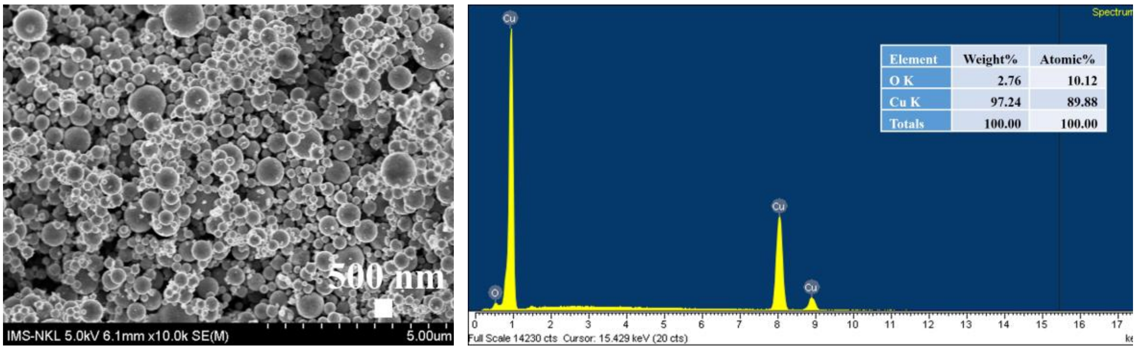


Figure 2. *Experimental layout for evaluating infrared emission characteristics.*

3. RESULTS AND DISCUSSION

3.1. Investigation of the shape and properties of Cu nanoparticles

SEM image of Cu nanoparticles prepared by the thermal plasma method (figure 3 (a)) provide information on the size, morphology, and distribution of Cu particles: The image has a scale of 500 nm, showing that Cu nanoparticles have sizes ranging from a few tens of nanometers to a few hundreds of nanometers; the average particle size is in the range of 100 ÷ 200 nm. The particles have a nearly round or spherical shape, which is common in particles prepared by the thermal plasma method. The particle surface is smooth, with no signs of sharp edges or large defects. The particles have a relatively uniform distribution, but there is also a phenomenon of concentration into small clumps. There may be slight agglomeration between nanoparticles, which is common during the fabrication process and after processing.



Element	Weight%	Atomic%
O K	2.76	10.12
Cu K	97.24	89.88
Totals	100.00	100.00

a) *b)*

Figure 3. *SEM image (a) and EDX (b) of nano Cu fabricated by thermal plasma method.*

The EDX plot showed peaks corresponding to the crystal structure of Cu material shown in Figure 3 (b). The most prominent peak is located at about 1 keV on the x-axis, and two lower peaks at 8.1 keV and 8.9 keV, labeled as ‘Cu’, indicate the presence of Cu material. There is only one very small peak at about 0.5 keV labeled as ‘O’, indicating the presence of oxygen. The table on the right lists the elements along with their mass percentage and atomic percentage in the sample. Of which, copper (Cu) has the largest proportion, accounting for 97.24% by weight and 89.88% by atomic percentage. Oxygen (O) accounts for 2.76% by weight and 10.12% by atomic percentage. This result shows that the material obtained after the fabrication process by the thermal plasma method is pure Cu nanoparticles, with only a very small amount of Oxygen (accounting for 2.76% by weight) as a result of the oxidation process of Cu when exposed to air.

3.2. Thermal images of Cu nanomaterial-coated samples

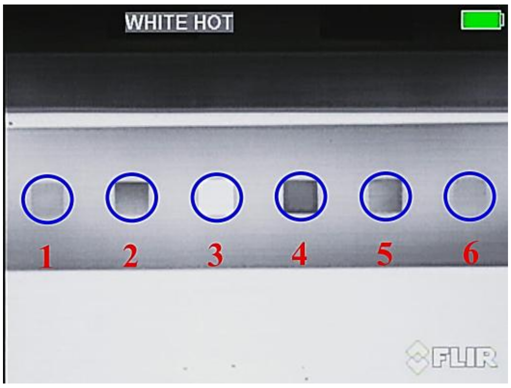


Figure 4. *Thermal images of samples coated with Cu nanomaterials with different concentrations: Samples (1) and (2) Prepared 30 minutes dispersion time (10 wt.% and 50 wt.% Cu, respectively); (2) Hole punching; (6) Polyurethane-only; Samples (4) and (5) Prepared 60 minutes dispersion time (10 wt.% and 50 wt.% Cu, respectively.*

Figure 4 shows thermal images of mica substrates coated with Cu nanomaterials at various concentrations and dispersion times. The images were captured in "White Hot" mode, where darker regions correspond to lower infrared emission. The samples prepared with 30 30-minute dispersion time (10 wt.% and 50 wt.% Cu at positions 1 and 2, respectively) are significantly darker than the Hole punching (position 3) and the polyurethane-only control (position 6). This observation indicates a reduction in infrared emission, which is more pronounced in the 50 wt.% Cu sample. The emission suppression effect is even more evident for the samples dispersed for 60 minutes. The 10 wt.% Cu coating (position 4) displays a distinct dark gray color, while the 50 wt.% Cu coating (position 5) appears nearly black, signifying a substantial decrease in emissivity. In contrast, the control samples (positions 3 and 6) remain bright white, reflecting their high emissivity and poor camouflage capability. These qualitative observations corroborate the quantitative emission spectra data, confirming that increased Cu concentration and longer dispersion times enhance the reduction of thermal emission.

3.3. Emission spectra of Cu nanomaterial-coated samples

The emission spectrum of the material samples was investigated using the SR5000N Spectroradiometer. The measurement result graph is shown in figure 5. *Cu10%_30p_50C* and *Cu50%_30p_50C*: These were two mica samples coated with a nano-Cu emissivity reduction film. The main difference between these two samples was the different Cu concentrations (10% and 50%). This will directly affect the heat absorption and emission capabilities of the coating. *Dungmoi_50C*: This mica sample was only coated with a pure PU layer, without nano-Cu. This helps us compare the effectiveness of nano-Cu coating in reducing emissions. *Mika_50C*: This was a mica sample without any film coating, which acts as a control sample to compare with the coated samples. *BB50C*: This was the emission spectrum of an absolute black body at 50 °C. This curve is used as a standard to compare with actual samples.

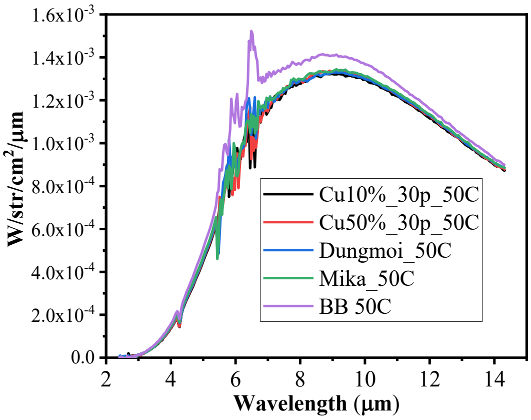


Figure 5. *Thermal emission spectra of Cu nano-coated samples with 30-minute dispersion time.*

The graph in figure 5 showed the emission spectra of the samples in the infrared region (about 2.5 ÷ 14.3 µm). The samples all have emission peaks at different positions. The position of this peak depends on the temperature of the object and the material properties. The emission intensity of the samples was different, indicating the difference in their thermal emission ability. In addition, Figure 5 also shows the comparison results between the samples. Both nano-coated samples *Cu10%_30p_50C* and *Cu50%_30p_50C* have lower emission intensity than samples *Dungmoi_50C* and *Mika_50C*, especially in the long wavelength region. This shows that nano-coated Cu has helped reduce the thermal emission ability of mica. In addition, the *Cu50%_30p_50C* sample has a slightly lower emission intensity than the *Cu10%_30p_50C* sample, indicating that increasing the Cu concentration can further reduce the thermal emission ability. The nano-coating Cu reduces thermal emission, a critical property for thermal camouflage applications. This effect is attributed to two primary mechanisms: *(i)* strong short-wavelength (UV-Vis) absorption via localized surface plasmon resonance [7], and *(ii)* inherently low energy absorption in the infrared (IR) region. A key feature of these coatings is their low IR emissivity, which minimizes radiated heat from the surface [8]. Consequently, this characteristic significantly hinders detection by thermal imaging systems. On the other hand, all the above samples have lower emission intensity than the absolute black body at the same temperature. This is because the actual materials are not absolute black bodies.

4. CONCLUSIONS

In summary, the above research results have shown that coating metal nanoparticles, especially copper (Cu) nanoparticles, on substrates such as mica can significantly reduce thermal emissivity. Thermal imaging analysis showed that samples coated with Cu nanoparticles at higher concentrations have lower emissivity, especially in the long-wavelength region, resulting in better thermal camouflage performance. Experiments with different Cu concentrations also confirm that coatings with high Cu nanoparticle concentrations tend to reduce thermal emissivity more. This result demonstrates the ability of Cu metal nanomaterials to modulate the thermal emissivity of the surface, reducing the detection ability through thermal imaging devices. Cu nano-coating significantly reduces emissivity, enabling practical advancement in adaptive thermal camouflage technologies.

A limitation of this study is that experiments were only conducted on a rigid laboratory substrate (mica), which provides ideal conditions for initial evaluation but does not fully represent flexible or practical materials used in real camouflage systems. Future work will therefore extend the investigation to flexible substrates such as polyester or nylon, as well as assess the stability of Cu nanocoatings under realistic environmental conditions. Such studies are expected to enhance both the applicability and durability of thermal camouflage coatings in military and civilian contexts.

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TÓM TẮT

Nghiên cứu chế tạo hạt nano đồng bằng phương pháp plasma nhiệt và ứng dụng trong ngụy trang nhiệt

Trong nghiên cứu này, chúng tôi đã khảo sát quá trình phủ lớp nano kim loại Cu lên chất nền mica giúp giảm khả năng phát xạ nhiệt nhằm ứng dụng trong ngụy trang nhiệt. Các hạt nano Cu được chế tạo bằng phương pháp Plasma nhiệt với kích thước trung bình khoảng 100 ÷ 200 nm. Cấu trúc, hình thái, thành phần và tính chất của hạt nano Cu được mô tả bởi kính hiển vi điện tử quét (SEM), phổ tán sắc năng lượng tia X (EDX), quang phổ hồng ngoại biến đổi Fourier (FTIR). Khảo sát, đánh giá đặc tính phát xạ hồng ngoại sau khi phủ các lớp nano kim loại Cu lên chất nền mica được đo bằng máy đo quang phổ bức xạ SR5000N, vật đen tuyệt đối SR800N-7° và camera ảnh nhiệt Flir Armasight. Kết quả cho thấy hai mẫu vật liệu với nồng độ Cu 10% và Cu 50% đều có cường độ phát xạ thấp hơn so với các mẫu còn lại đặc biệt là ở vùng bước sóng dài. Điều này cho thấy việc phủ nano Cu đã giúp giảm khả năng phát xạ nhiệt của mica. Kết quả này cho thấy khả năng của vật liệu nano kim loại trong việc điều chỉnh độ phát xạ nhiệt của bề mặt, làm giảm khả năng phát hiện qua thiết bị ảnh nhiệt ứng dụng trong ngụy trang ảnh nhiệt.

Từ khoá: Ứng dụng ngụy trang nhiệt; Giảm phát xạ nhiệt; Phủ hạt nano kim loại; Hạt nano Cu.