Experimental research and evaluation of thermal camouflage effectiveness of advanced materials for mobile vehicles

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ABSTRACT

Mobile vehicles, with high heat-generating engines and metallic outer shells known for their significant heat absorption and emission, are easily detected and identified by thermal imaging reconnaissance systems. To mitigate thermal contrast, a practical solution is to apply coatings capable of reducing thermal emissions from mobile vehicles. However, no domestic studies have yet evaluated the effectiveness of thermal camouflage coatings for such vehicles. This paper focuses on analyzing the composition of advanced coating materials, conducting experimental trials, and assessing their thermal camouflage effectiveness for mobile vehicles in Vietnam. The findings of this study serve as a foundation for developing new materials and effectively applying thermal camouflage to mobile vehicles in the country.

Keywords: Camouflage; Thermal camouflage; Mobile vehicles; Emission energy; Gray level similarity.

1. INTRODUCTION

Future localized wars are expected to be hightech conflicts involving coordinated operations among air, land, and sea-based weapon. Among these, mobile vehicles play a critical role in shaping the outcome of battles. However, with the rapid advancement of reconnaissance technologies and the sophistication of modern weaponry, the survivability of mobile vehicles is increasingly at risk. This situation demands measures to enhance the survivability of these targets, with camouflage emerging as a long-established, highly effective solution and continues to evolve as a global development trend [1, 2].

As a result, many countries are now actively researching, developing the field of camouflage and application into for various targets, including soldiers, weapons, equipment, and especially mobile vehicles. In major powers such as Russia, the United States, and NATO member states, camouflage products for mobile vehicles have been under development for a long time. These products have not only been deployed over extended periods but are also continuously improved and further advanced. The main purpose is to counter enemy thermal reconnaissance, making high-tech weapons less effective [3, 4].

In the world, camouflage products for mobile vehicles are highly diverse, including those designed for visible light regions, thermal imaging regions, and multispectral camouflage. However, the current development trend focuses on thermal imaging and multispectral camouflage products. These solutions primarily operate on the principle of reducing the infrared radiation intensity of the target, thereby minimizing the radiation contrast with the background and making mobile vehicles blend more seamlessly into their surroundings. It is estimated that the comprehensive effectiveness of such camouflage measures can reduce by more than 90% the infrared radiation of a target [5, 6].

Modern thermal reconnaissance devices operate within spectral bands of 3 – 5 µm and 8 – 14 µm. Consequently, studies on thermal camouflage for targets also focus on evaluating effectiveness within these spectral bands. Thermal camouflage methods include: Altering the infrared radiation characteristics of the target to ensure its infrared radiation falls outside the atmospheric window or the wavelength bands used by infrared-guided missiles. Reducing the intensity of the target's infrared radiation by lowering its temperature and employing materials with low emissivity. Controlling the transmission of the target's infrared radiation by enhancing absorption, scattering, and reflection during transmission to modify the energy distribution of the target's radiation. Disrupting the infrared radiation signals of the target by creating illusions [7].

Among these methods, reducing the infrared emission intensity of the target is the most commonly used approach. This can be achieved through two primary measures: first, by using shielding covers to lower the surface temperature, and second, by applying low-emissivity materials directly onto the target's surface [8, 9]. The use of low-emissivity materials is often developed specifically for direct application to mobile vehicle surfaces. This represents a high-tech solution for thermal camouflage, yet no domestic research studies in this area have been published to date. Currently, camouflage for mobile vehicles in Vietnam typically involves the application of conventional paints with colors and patterns designed to match forested or mountainous terrains for visible light camouflage. Therefore, researching, developing, and evaluating the thermal camouflage effectiveness of advanced materials for domestic mobile vehicles is an urgent and very meaningful task.

In this study, the research team conducted an analysis of the components of thermal camouflage materials using laboratory techniques such as SEM, EDX, and X-ray diffraction spectroscopy. Additionally, the materials were applied to vehicles, and their thermal camouflage effectiveness was tested in the field. The evaluation focused on criteria such as surface temperature reduction, emitted energy attenuation, and grayscale similarity of thermal images. The research results are presented specifically in the following sections of the paper.

2. THEORETICAL BASIS AND EXPERIMENTAL METHOD

2.1. Theoretical basis

In the world, since the 1960s, the infrared emission characteristics of mobile targets have been studied worldwide, focusing on the infrared thermal emissions characteristics of the engine and other critical factors influencing the overall thermal radiation of the vehicle. The United States and the Soviet Union conducted extensive research on various infrared suppression technologies, including infrared radiation shielding, high-speed airflow cooling, convective air-film cooling, the application of thermal insulation materials, incomplete combustion techniques,...

To develop effective thermal camouflage solutions, it is essential to delve into the nature of infrared radiation and gain a deeper understanding of its characteristics. Infrared radiation is a part of the electromagnetic spectrum, with wavelengths ranging from 0.76 µm to 1000 µm. Thermal imaging-based target detection relies on infrared radiation characteristics within the wavelength range of 3 µm to 15 µm. In this range, infrared detectors primarily identify thermal radiation emitted by the target and its background, using the radiation contrast to determine the target. This method is thus referred to as thermal infrared detection. Due to atmospheric attenuation during transmission, only specific wavelengths can pass through the air without significant energy loss. These wavelengths correspond to the practical operating ranges of modern infrared detectors, covering spectral regions of 3 µm to 5 µm and 8 µm to 14 µm, commonly referred to as the atmospheric window regions [10, 11].

As is well known, when the temperature of any object exceeds 0K (-273.15 °C), thermal energy is converted into radiation energy. The characteristics of this radiation depend on the object's temperature, surface roughness, and color. For objects with temperatures below 800 °C, the emitted radiation predominantly falls within the infrared spectrum. When infrared radiation interacts with the surface of an object, three phenomena typically occur: transmission, absorption and reflection. Assuming the incident power is P_i, the transmitted power is P_r, the absorbed power is P_a, and the reflected power is P_p, the relationship between these quantities is given by:

$$P_i = P_r + P_a + P_p \tag{1}$$

$$\frac{P_r}{P_i} + \frac{P_a}{P_i} + \frac{P_p}{P_i} = 1 \tag{2}$$

Definition: P_r/P_i is defined as the "transmission ratio" r; P_a/P_i as the "absorption ratio" a; and P_p/P_i as the "reflection ratio" p. Therefore, the relationship can be expressed as: r + a + p = 1. For opaque objects, since the transmission ratio r = 0, the equation simplifies to: a + p = 1. This means that for opaque objects, the higher the absorption rate, the lower the reflection rate, and vice versa. According to Kirchhoff's law, objects that absorb strongly will also emit strongly. Hence, it can be inferred that an object with high emissivity will have low reflectivity. The ratio between the emissivity coefficient and the absorption coefficient is independent of the material's properties and depends only on temperature and wavelength. However, different materials will exhibit different emissivity coefficients [12].

The radiation energy of a target depends on its surface temperature and emissivity. Therefore, to blend the target with the background, it is necessary to minimize the temperature difference between the two. If matching temperatures is not feasible, the surface emissivity of the target must be reduced to compensate for the temperature disparity. Principle of Thermal Camouflage: According to Stefan-Boltzmann's law [13], for opaque objects, the radiation intensity is determined by the following formula:

$$E_0 = \frac{G}{\pi} \cdot \varepsilon_r \cdot T^4 \tag{3}$$

Where, E_0 (W/m^2/str) represents the radiative energy; $G = 5.67\times10^{-8}$ W/m^2/K^4 is the Stefan-Boltzmann constant; ε_r is the emissivity of the target and T (K) is the absolute temperature.

This formula highlights that both emissivity and temperature significantly impact the thermal radiation of a target, providing the foundation for thermal camouflage strategies. The key to thermal camouflage lies in controlling the surface temperature and emissivity of the target. According to Stefan-Boltzmann's law, the radiation intensity of a target is proportional to the fourth power of its temperature. Therefore, the most effective way to achieve infrared invisibility is to control the target's surface temperature and minimize the temperature difference between the target and the background [14, 15].

However, achieving the necessary temperature parity between the target and the background is often challenging. As a result, advanced camouflage materials must be employed to adjust the target's surface emissivity. By modifying the target's infrared radiation to match that of the background, the radiation contrast can be reduced to nearly zero, making it difficult for thermal imaging reconnaissance systems to detect the target, then, the camouflage achieves effectiveness.

2.2. Experimental method

The research team prepared a material sample labeled: Anti-Thermal (AT) (figure 1a). The material was mixed and then spray-coated onto the entire body and tracks of the mobile vehicle. The vehicle was stored in a shaded area with a roof for seven days to allow the coating to dry naturally, avoiding direct exposure to harsh sunlight. This process ensured optimal adhesion of the coating to the vehicle’s surface (figure 1b).

The analysis of the camouflage material composition was carried out in the laboratory of the Institute of Materials Science – Vietnam Academy of Science and Technology. The equipment used included: High-resolution transmission electron microscope (HR-TEM) JEM2100 (Jeol, Japan); Hitachi S-4800 electron microscope; X-ray diffraction (XRD) model D8 Advance (Bruker AXS, Germany).

a) AT material; *b) Mobile vehicle after coating with AT material.*

***Figure 1.** Experimental samples.*

The field experiment was conducted with the support of the SR5000N spectral emission energy meter, with a working spectrum range from 2,39 µm to 14,34 µm to collect spectral data. Image data was collected by a Moskito TI dedicated camera integrated with a multi-channel receiver with three observation modes: daytime optical mode, low-light imaging mode and thermal imaging mode; with the following thermal imaging channel parameters: resolution 640×480, field of view 12°, working spectrum range from 8 µm to 14 µm.

3. EXPERIMENTAL RESULTS AND EVALUATION

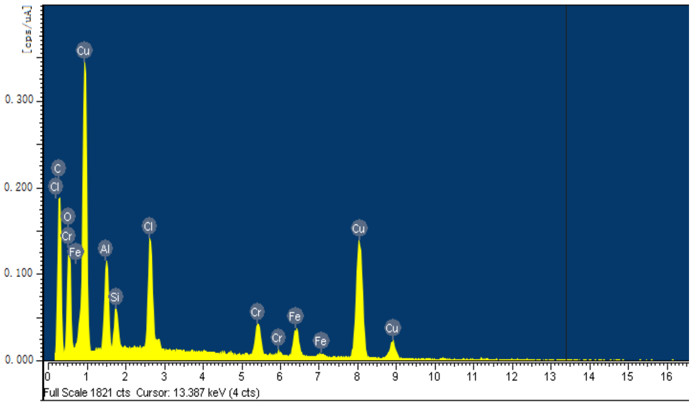
3.1. Laboratory analysis results

To determine the structural composition and the ratio of elements in the material sample, the research team applied EDX measurements using a Hitachi S-4800 electron microscope and an X-ray diffraction spectrum analyzer (XRD); at the same time, they applied SEM (Scanning Electron Microscope) technique on a JEM-2100 electron microscope to determine the size of the particles. The results are shown in figure 1.

The EDX analysis (figures 2a, 2b) shows that the Anti-Thermal (AT) material comprises both metallic and non-metallic elements. Copper (Cu) is the dominant metal, accounting for 29.21%, along with smaller amounts of Aluminum (Al), Iron (Fe), and Chromium (Cr), these metals contribute to the material's thermal and mechanical properties. Among non-metals, Carbon (C) and Oxygen (O) have the highest mass fractions, at 39.79% and 15.65%, respectively, with trace amounts of Chlorine (Cl) and Silicon (Si), likely influencing the material's bonding characteristics and surface properties. This composition is optimized for thermal emissivity control and structural durability, ensuring effective thermal camouflage.

The SEM images of the AT material (figure 1c) reveal particles of varying sizes, predominantly in the micrometer and nanometer range. To further investigate the molecular bonds and compounds within the material, an X-Ray Diffraction analysis was conducted, with the results presented in figure 1c. The XRD spectrum analysis reveals that the strongest diffraction peaks appear at $2\theta = 43.7^o$ and $2\theta = 50.4^o$, confirming the presence of pure copper (Cu) as a major component in the AT material sample. Some diffraction peaks appear at $2\theta = 38.5^o$ and $2\theta = 44.8^o$ are characteristic of aluminum (Al), while peaks at $2\theta = 33{,}4^o$ and $2\theta = 35{,}8^o$ indicate the presence of iron oxide (Fe_2O_3). Additionally, minor diffraction peaks at $2\theta = 31^o$ và $2\theta = 36{,}5^o$ are characteristic of the mixed oxide compound Fe.Al.O.

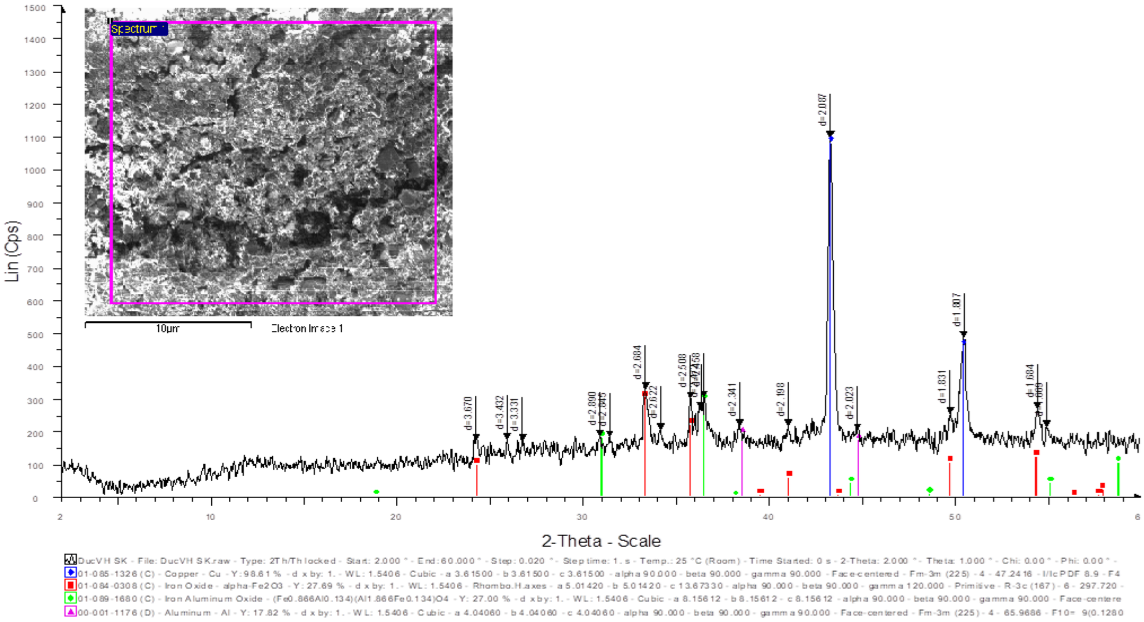
In summary, after analyzing AT material samples using laboratory equipment, it was determined that: Single metal nanoparticles of Cu, Al, Cr and Fe, Al in oxide form mixed in a matrix made of non-metallic elements such as C, O, Cl,... create materials with oriented applications in camouflage.



a) Compositional analysis by EDX measurement;

Element	Weight%	Atomic%
C K	39.79	64.04
O K	15.65	18.91
Al K	4.06	2.91
Si K	1.31	0.90
Cl K	4.16	2.27
Cr K	2.69	1.00
Fe K	3.12	1.08
Cu K	29.21	8.89
Totals	100.00	

b) Analysis of the proportions of the constituent elements;



c) X-ray diffraction analysis and size measurement by electron microscope.

Figure 1. *Analysis results of anti-thermal material sample.*

3.2. Experimental results

3.2.1. Surface temperature difference

a) Vehicle covered with AT material; *b) Vehicle covered with regular paint.*

Figure 2. *Using a thermometer to check the surface temperature of the vehicle.*

As analyzed, temperature is a critical factor significantly influencing the radiation energy of a target. Therefore, evaluating the reduction in surface temperature of a target is a key indicator for assessing the effectiveness of thermal camouflage materials applied to mobile vehicles. In this study, the research team measured the surface temperatures of two vehicles: one coated with the AT material and the other using regular paint (figure 2).

The versatile UNI-T UT 202+ device was used to measure surface temperature using the contact method. Results after 10 measurements at one location were counted, averaged and shown in table 1.

Table 1. *Vehicle surface temperature.*

Measurement location	**Surface temperature, ºC**	
	Vehicle covered with AT material	Vehicle covered with regular paint
Side of the vehicle	40	44
Front of the vehicle	46	53
Rear of the vehicle	45	51

The measurement results indicate a temperature difference between the two vehicles at the same locations on their surfaces (table 1). Specifically, the surface temperature of the vehicle coated with AT material is 4 – 7 °C lower than the vehicle with regular paint, varying by location.

In the preliminary evaluation, the research team concluded that the AT camouflage coating effectively reduces the vehicle's surface temperature, thereby decreasing its radiation energy. This indicates its potential to meet the requirements for thermal camouflage of vehicles under Vietnam's conditions. To verify this conclusion, the team will conduct further experiments.

3.2.2. Spectrum data analysis

In this study, the research team utilized the SR5000N spectral radiometer to measure the emission energy of the background and two vehicles: one coated with the AT material and the other with its regular paint [16, 17]. The spectral data from 20 measurements were averaged and plotted, as shown in figure 3.

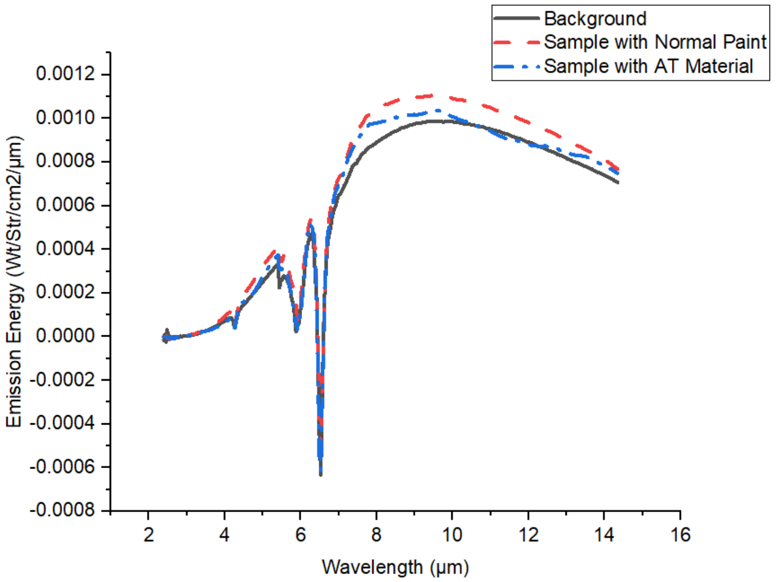


Figure 3. *Spectrum data analysis results.*

The total emission energy levels are calculated and detailed in table 2.

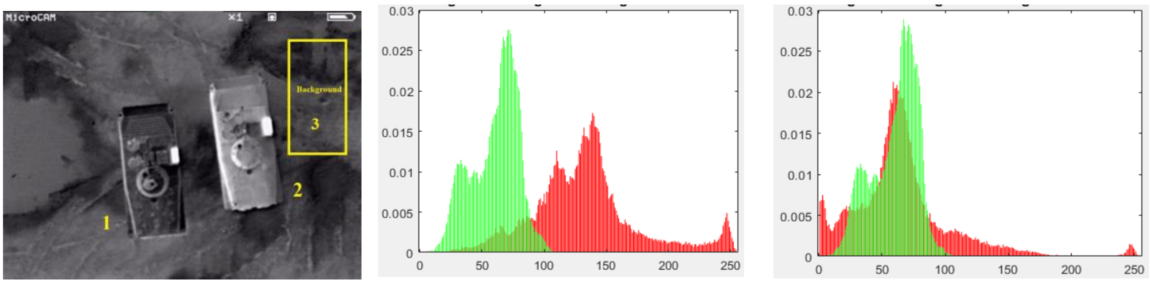
Table 2. *Total energy over wavelength bands.*

Target	**Total energy over wavelength bands, Wt/Str/cm^2**	
	From 3 µm to 5 µm	From 8 µm to 14 µm
Vehicle with regular paint	2,106x10^{-4}	6,054x10^{-3}
Vehicle with AT material	1,670x10^{-4}	5,584x10^{-3}
Background	1,648x10^{-4}	5,441x10^{-3}

The calculations show that the emission energy reduction for the vehicle coated with the AT material is approximately 21% in the 3 – 5 µm wavelength range and around 8% in the 8 – 14 µm range, compared to the vehicle with standard paint. Additionally, the emission energy levels are nearly equivalent to those of the background.

3.2.3. Image data analysis

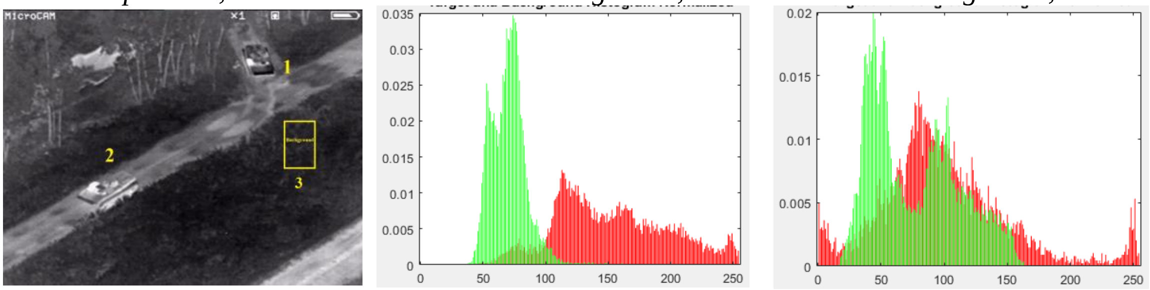
To conduct a detailed and accurate evaluation of the thermal camouflage effectiveness of the AT material, the research team carried out test runs and compared thermal images captured by a thermal camera. The images of the vehicle coated with the AT material (vehicle 1) were analyzed alongside those of the vehicle with regular paint (vehicle 2). The test runs were conducted under controlled conditions at the training field.



a) Vehicles at starting position;

b) Vehicle 2 overlaps 16% with the background;

c) Vehicle 1 overlaps 71% with the background;



d) Vehicles are moving on the road;

e) Vehicle 2 overlaps 12% with the background;

f) Vehicle 1 overlaps 67% with the background.

Figure 4. *Image data analysis results.*

The thermal images captured after ignition at the starting position (figure 5a) show a clear distinction between the two vehicles. The vehicle coated with the AT material appears dark, blending with the background, while the vehicle with standard paint is bright and stands out prominently against the background. Gray-level histogram analysis indicates that the similarity of vehicle 2 to the background is only 16% (figure 4b), whereas the similarity for vehicle 1 reaches 71% (figure 4c).

When observing the images of both vehicles moving along the test track (figure 4d), the results reveal the following: for vehicle 1, most of the body appears dark and blends well with the background, except for the exhaust area near the engine compartment, which shows a brighter. In contrast, vehicle 2 appears almost entirely bright and prominently stands out against the background. Image analysis and comparison of gray-level histograms indicate that the similarity of vehicle 2 to the background is only 12% (figure 4e), whereas vehicle 1 maintains a similarity of 67% (figure 4f).

In summary, applying the AT material increases the gray-level similarity between the vehicle and the background. This demonstrates that the AT coating significantly enhances the vehicle's ability to blend with the background when observed through thermal imaging equipment.

4. CONCLUSIONS

A study analyzing and experimentally applying advanced materials to address the challenge of multispectral camouflage for mobile vehicles is presented in this paper. The analysis reveals that AT material, composed of single element and oxide nanometal particles blended into a nonmetallic matrix, is well suited for use as a surface coating to enhance the camouflage performance of mobile vehicles. Experimental evaluation demonstrated that applying the AT material reduces the surface temperature of mobile vehicles by 4 – 7 °C and decreases the emission energy by up to 21%, bringing it close to the emission energy of the background. Thermal imaging observations reveal that the AT coating significantly enhances the visual similarity between mobile vehicles and their background, with gray-level similarity increasing from 12% to 71%. The findings of this study confirm the effectiveness of the AT material in thermal camouflage for mobile vehicles.

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TÓM TẮT

Nghiên cứu thử nghiệm và đánh giá hiệu quả ngụy trang ảnh nhiệt của vật liệu tiên tiến cho phương tiện cơ giới

Các phương tiện cơ giới có động cơ sinh nhiệt cao và lớp vỏ thường được làm bằng các vật liệu kim loại có khả năng hấp thụ và phát xạ nhiệt lớn. Vì lý do đó nên các hệ thống trinh sát ảnh nhiệt có thể dễ dàng phát hiện hoặc nhận dạng mục tiêu. Để giảm độ tương phản nhiệt, một phương pháp hữu hiệu là áp dụng lớp phủ có khả năng làm suy giảm phát xạ nhiệt từ các phương tiện cơ giới. Tuy nhiên, trong nước hiện vẫn chưa có nghiên cứu nào đánh giá hiệu quả của lớp phủ ngụy trang nhiệt cho các phương tiện cơ giới. Do đó, bài báo này đã tập trung vào việc nghiên cứu phân tích thành phần vật liệu phủ tiên tiến, đồng thời áp dụng thử nghiệm và đánh giá hiệu quả ngụy trang ảnh nhiệt của nó cho phương tiện cơ giới tại Việt Nam. Kết quả của bài báo sẽ là cơ sở để nghiên cứu chế tạo vật liệu mới và áp dụng ngụy trang ảnh nhiệt hiệu quả cho các phương tiện cơ giới trong nước.

Từ khoá: Ngụy trang; Ngụy trang ảnh nhiệt; Phương tiện cơ giới; Năng lượng phát xạ; Tương đồng mức xám.