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THERMAL BEHAVIOR OF THE HIERARCHICAL STRUCTURE OF MORPHO DIDIUS BUTTERFLY WINGS: IMPLICATIONS FOR PASSIVE INFRARED SIGNATURE MANAGEMENT

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Abstract: *Modern surveillance and detection systems increasingly rely on thermal imaging cameras that detect objects based on temperature differences between the target and the surrounding environment. Military vehicles are particularly vulnerable to this type of detection due to significant heat generation from engines, mechanical friction, and exhaust systems, as well as heat transfer to external structural surfaces. As a result, these vehicles often exhibit a pronounced infrared (IR) signature, making them easily detectable under low-visibility or nighttime conditions.*

Recent research has therefore focused on natural structures exhibiting distinctive thermal behavior that may provide principles for passive infrared signature management. In this study, the hierarchical structure and thermal behavior of Morpho didius butterfly wings were investigated using scanning electron microscopy, digital holographic interferometry, differential scanning calorimetry, and infrared thermal imaging. The results revealed pronounced structural and thermal heterogeneity, including temperature-dependent heat capacity, non-uniform surface temperature distribution, and localized thermal inertia under external heating. These findings indicate that the hierarchical organization of the wing strongly influences heat storage, transfer, and spatial temperature distribution.

The identified structure–property–response relationship provides design principles for the development of bioinspired materials and surfaces capable of controlling heat distribution and delaying thermal equilibration. Such architectures may contribute to reduced infrared contrast under transient thermal conditions, providing a potential basis for passive thermal management and infrared signature reduction in military and other defense platforms.

Keywords: *IR signature reduction, thermal imaging detection, thermal masking, military vehicle protection, biomimetic material.*

1. INTRODUCTION

The continuous advancement of thermal imaging technology has greatly improved the performance of modern surveillance, reconnaissance, and target acquisition systems. In contrast to conventional optical sensors, thermal cameras detect infrared radiation emitted by objects according to their surface temperature. This capability allows reliable operation at night, in poor visibility, and under adverse weather conditions. As a result, thermal imaging has become one of the most effective methods for detecting, identifying, and tracking military vehicles on the modern battlefield [1, 2].

As thermal imaging sensors continue to improve in sensitivity and detection range, reducing the infrared (IR) signature of military vehicles has become increasingly important. [3] A vehicle's IR signature is primarily generated by heat sources such as the engine, exhaust system, tracks, and heated external surfaces, which can be detected by modern thermal sensors even under low-visibility conditions. [4] Effective IR signature reduction decreases the probability of detection, identification, and

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tracking by enemy surveillance systems and infrared-guided weapons, thereby improving vehicle survivability on the battlefield.

A wide range of techniques has been proposed to mitigate the infrared signature of military platforms, including thermal barrier materials, low-emissivity coatings, exhaust suppression systems, active thermal management, and adaptive camouflage technologies. Although these approaches can substantially decrease the detectability of a target in the infrared spectrum, many of them introduce additional challenges related to system weight, power demand, operational complexity, and maintenance. As a result, recent research has increasingly focused on passive infrared signature management solutions based on advanced materials and engineered surface structures. [5]

Nature offers numerous examples of highly effective thermal regulation mechanisms that have evolved to help organisms survive in diverse and often extreme environments. Many biological systems possess sophisticated hierarchical structures that enable precise control of heat absorption, insulation, dissipation, and redistribution across multiple length scales. Inspired by these naturally optimized solutions, researchers have increasingly explored bioinspired design strategies for the development of advanced materials with tailored thermal properties. [6, 7] Such approaches provide valuable opportunities for creating passive thermal management and infrared camouflage materials capable of regulating surface temperature and heat transfer without external energy input.

In this work, several biological structures known for their distinctive thermal characteristics were examined to explore mechanisms that could be applied to infrared signature management. Experimental thermal analyses were conducted to evaluate their ability to influence heat accumulation, transfer, and spatial temperature distribution. By identifying the underlying principles responsible for these thermal responses, the study aims to contribute to the development of bioinspired materials and surface designs for passive thermal control. Such solutions may offer promising opportunities for reducing the thermal detectability of military vehicles and improving their survivability against modern infrared surveillance and targeting systems. [8]

2. MATERIALS AND METHODS

2.1. Biological Sample

The biological sample investigated in this study consisted of wings of the butterfly *Morpho didius*. The specimens were stored under ambient laboratory conditions in sealed glass containers, without any additional preparation prior to the experiments. The analyses were performed directly on the preserved wings.

Morpho didius was selected because of its highly ordered hierarchical wing architecture, which has been extensively recognized for its unique optical and structural properties. [9] The wing surface is covered with overlapping scales composed of complex micro- and nanoscale features, including multilayered ridge-lamella structures and air gaps. Beyond their well-known role in structural coloration, these nanostructures are expected to influence heat transfer, heat storage, and the spatial distribution of temperature across the wing surface. Their combination of geometry and material organization makes *Morpho didius* an attractive biological model for investigating passive thermal regulation mechanisms relevant to bioinspired infrared signature management.

2.2 Morphological Characterization

Standard microscopic techniques were employed as supporting methods for the characterization of the wing surface morphology (Figure 1). The microstructural features of the *Morpho didius* wings were analyzed using a scanning electron microscope (SEM), JEOL JSM-6610 LV (Japan). SEM imaging was performed in order to resolve the hierarchical micro- and nanoscale architecture of the wing surface. These observations provide a structural basis for interpreting the thermal behavior of the wing in subsequent analyses.

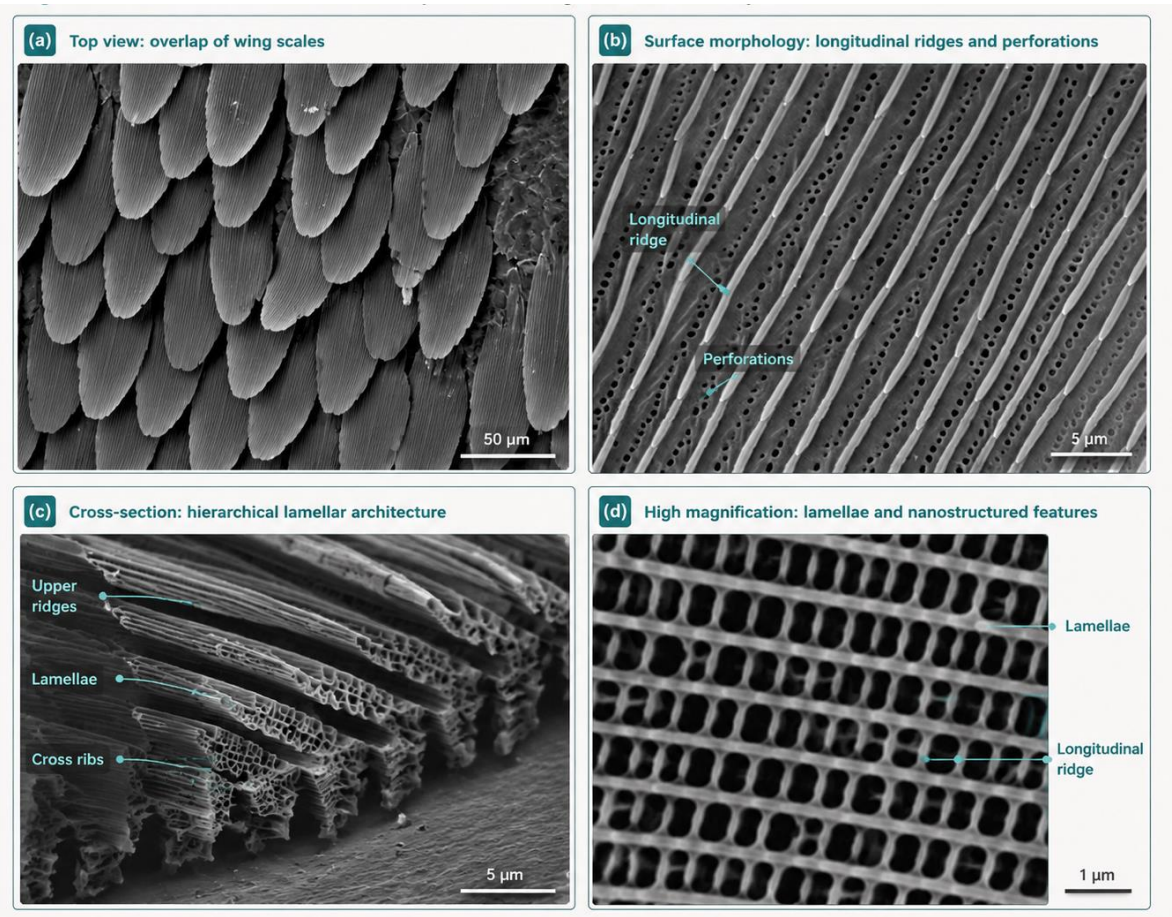


Figure 1. Scanning electron microscopy (SEM) characterization of *Morpho didius* wing scales at multiple hierarchical levels.

(a) Top-view of overlapping cover scales illustrating their roof-like arrangement.
(b) Surface morphology of an individual scale showing longitudinal ridges and perforated architecture.
(c) Cross-sectional view revealing the multilayered ridge–lamella organization responsible for the hierarchical microstructure.
(d) High-magnification image of the lamellar architecture, highlighting the periodic structural features that contribute to the wing's optical and thermal behavior.

In addition to SEM analysis, digital holographic interferometry was employed as a complementary technique for structural characterization of the *Morpho didius* wing. [9] Holography enables the recording of object deformation between two states of exposure, providing full-field, three-dimensional information about structural changes. In this study, it was used to monitor the dynamic response of the wing microstructure under external thermal stimulation. This approach allows observation of nanoscale displacements induced by heating in real time, providing insight into the mechanical and structural behavior of the hierarchical wing architecture. A simplified holographic setup was used for the measurements, while the general configuration of the system has been described elsewhere [10, 11].

2.3 Thermal Characterization

Differential scanning calorimetry (DSC) analysis was performed to determine the heat capacity of *Morpho didius* wing samples. Measurements were carried out using a DSC Q1000 instrument (TA Instruments, Delaware, USA). The samples were analyzed over a temperature range of approximately 22-140 °C, following the standard procedure provided by the manufacturer and in accordance with ASTM E1269-11. The obtained data were used to evaluate the temperature-dependent thermal response of the biological material. Particular features of the heat-capacity curve were observed in the low-temperature range of approximately 22-30 °C and in the range of approximately 86-95 °C.

Infrared thermal measurements were performed in order to observe the surface temperature response of the *Morpho didius* wing under controlled external heating. A FLIR A65sc thermal camera was positioned in front of the sample to record temperature distribution during laser irradiation. The sample was illuminated using a low-power 532 nm laser source, providing controlled localized heating of the wing surface. Thermal images were recorded with a spatial resolution of 640 × 512 pixels and a frame rate of 30 Hz. The data were processed using FLIR ResearchIR Max software (v4.40), enabling analysis of temperature distribution and temporal evolution of the thermal response.

3. RESULTS AND DISCUSSION

3.1 Morphological structure of *Morpho didius* wing

The microstructural organization of *Morpho didius* wing samples was analyzed using scanning electron microscopy (SEM), revealing a highly ordered hierarchical architecture composed of overlapping scales with well-defined micro- and nanoscale features. The surface is characterized by periodic ridge-lamella structures forming a multilayered arrangement with embedded air gaps, which together generate a complex three-dimensional morphology. Such structural organization results in a highly anisotropic surface, where geometry varies significantly across different length scales.

The observed nanoscale features are arranged in a repeating pattern that contributes to the overall structural stability and functional behavior of the wing. In particular, the combination of ridge spacing, lamella thickness, and internal voids suggests a heterogeneous medium in which local structural variations may influence both mechanical and thermal transport processes. This hierarchical organization is a key characteristic of biological photonic structures and is not limited to optical functionality alone.

In addition to static morphological analysis, digital holographic interferometry was used as a complementary technique to observe the dynamic response of the wing structure under external thermal stimulation. The results indicate that localized regions of the wing exhibit measurable nanoscale displacements when subjected to heating, suggesting that the structure is not mechanically rigid at all scales but rather exhibits subtle thermally induced deformation behavior. This dynamic response further confirms the complexity of the hierarchical architecture and its sensitivity to external energy input.

Overall, the combination of SEM and holographic observations demonstrates that the *Morpho didius* wing possesses a multi-scale structural organization with both static and dynamic characteristics. Such hierarchical complexity is expected to play an important role in governing heat distribution and energy transport within the material, providing a structural basis for the thermal behavior analyzed in the following sections.

3.2 Heat capacity behavior of *Morpho didius* wing

The thermal response of *Morpho didius* wing samples was investigated using differential scanning calorimetry (DSC), and the resulting heat capacity (Cp) as a function of temperature is presented in Figure 2. The obtained curve exhibits a pronounced non-linear behavior over the investigated temperature range (20–140 °C), indicating a temperature-dependent thermal response of the biological material.

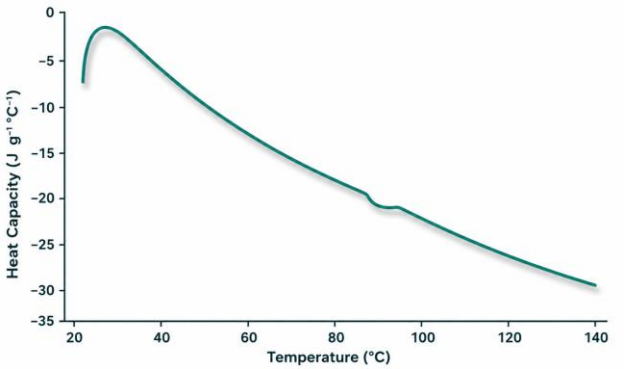


Figure 2. Heat capacity as a function of temperature for the *Morpho didius* wing obtained by differential scanning calorimetry (DSC). The observed nonlinear trend reflects the temperature-dependent thermal behavior of the hierarchical wing architecture and provides the basis for interpreting the subsequent infrared thermal response.

In the low-temperature region (approximately 22–30 °C), a pronounced change in heat capacity is observed, followed by a gradual decrease over the subsequent temperature range up to approximately 85 °C. This behavior may be associated with the relaxation of hierarchical micro- and nanoscale components within the wing architecture.

At approximately 86-95 °C, a distinct change in the slope of the curve is observed, followed by a continued gradual decrease in heat capacity toward 140 °C. This feature indicates a localized change in the thermal response of the material within this temperature range.

Overall, the non-linear temperature dependence of heat capacity indicates that the thermal response of the wing is not uniform over the investigated temperature range. The distinct changes observed in the approximately 22–30 °C and 86–95 °C regions suggest that different temperature intervals are associated with different thermal response characteristics of the biological material.

From an application perspective, such behavior is of particular interest for passive thermal regulation concepts, as temperature-dependent heat capacity may contribute to delayed heat propagation and reduced thermal contrast under transient heating conditions. These features are relevant for the design of bioinspired materials intended for infrared signature management.

3.3 Infrared thermal response

The infrared thermal response of the *Morpho didius* wing was investigated under controlled laser heating conditions using a FLIR A65sc thermal imaging camera. The recorded thermographic data provide a spatial and temporal representation of surface temperature distribution during external energy input, allowing analysis of heat propagation across the wing structure.

Upon laser irradiation, the wing exhibits a non-uniform temperature distribution, indicating heterogeneous heat absorption and dissipation across the surface. Localized regions respond differently to thermal excitation, resulting in spatial temperature gradients that reflect the underlying

hierarchical micro- and nanoscale architecture. The observed thermal behavior suggests that heat transfer within the structure is not homogeneous, but rather governed by localized structural variations.

Time-resolved thermal imaging further reveals that the cooling dynamics of the wing are non-uniform, with certain regions retaining heat for longer periods than others. This indicates the presence of localized thermal inertia, likely induced by structural complexity and air-trapped micro- and nanoscale features. Such behavior is consistent with the presence of multi-scale architectures that influence both heat storage and dissipation pathways.

The combination of spatial and temporal thermal variations observed in the FLIR measurements supports the existence of structure-dependent thermal regulation mechanisms within the wing. These findings are in agreement with the DSC results, which indicate temperature-dependent heat capacity behavior, suggesting that both macroscopic thermal response and thermodynamic properties are governed by the same hierarchical structural organization.

Overall, the infrared thermal response demonstrates that the *Morpho didius* wing does not behave as a thermally uniform material, but rather as a complex system with spatially varying heat transfer characteristics. This behavior is relevant for understanding passive thermal regulation in biological systems and may provide inspiration for the development of bioinspired materials for infrared signature management.

To integrate the morphological features, thermal properties, and observed infrared response into a unified interpretation, a schematic overview of the system behavior is presented in Figure 3.

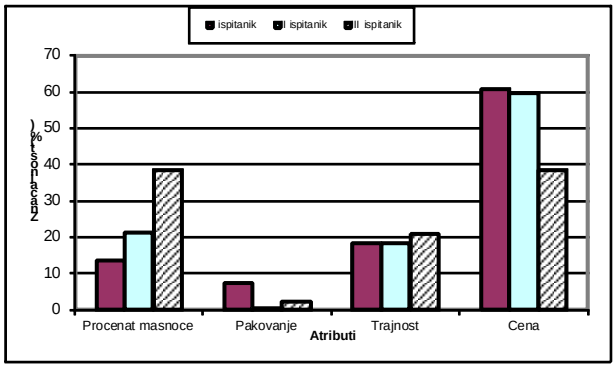


Figure 3. Structure-property-response framework illustrating how the hierarchical architecture of the *Morpho didius* wing governs its temperature-dependent thermal behavior and influences the apparent infrared response, providing inspiration for passive infrared signature management concepts.

4. ENGINEERING IMPLICATION

The observed structure–property–response relationship suggests design principles for bioinspired materials capable of advanced thermal regulation (Figure 4).

The observed thermal behavior may be particularly relevant to military platforms exposed to transient heating conditions, where infrared detectability is strongly influenced by the temperature distribution of external surfaces. The bioinspired approach proposed in this study could be translated into engineered multilayer or hierarchical surface structures designed to redistribute and temporarily store heat, thereby reducing local temperature gradients and delaying thermal equilibration. Such structures could potentially be incorporated into passive thermal-management layers, surface treatments, or camouflage-related materials applied to selected external components of military vehicles and other defense platforms. The present study does not experimentally demonstrate infrared signature reduction on a military vehicle; rather, it provides a biological model and experimentally observed structure–property–response relationships that may serve as a basis for the future design and testing of such materials under realistic military operating conditions.

Hierarchical architectures similar to those found in *Morpho didius* wings may enable a decoupling between bulk thermal properties and apparent infrared response, where the observed thermal signature is governed primarily by structural organization rather than homogeneous material behavior. Such mechanisms can lead to controlled heat storage and dissipation, resulting in reduced thermal contrast under transient heating conditions. This indicates that engineered surfaces based on similar principles could exhibit thermal behavior that is not directly representative of the overall system temperature, but instead reflects localized structural interactions with heat transfer processes. From an application perspective, such behavior is relevant for infrared signature management and the development of passive systems aimed at reducing thermal detectability of complex platforms.

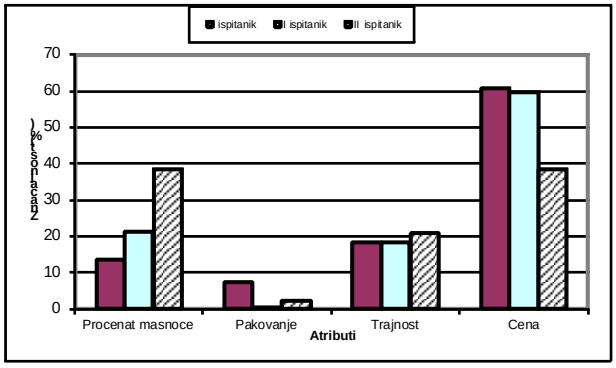


Figure 4. Bioinspired concept illustrating the relationship between hierarchical structural organization, heat redistribution, and apparent infrared response. The proposed mechanism demonstrates how structural design may govern thermal emission independently of bulk material properties, providing a framework for passive infrared signature management.

5. CONCLUSION

This study investigated the hierarchical structure and thermal behavior of *Morpho didius* butterfly wings to

identify structural principles relevant to passive thermal regulation and infrared signature management. The combined morphological and thermal analyses revealed a pronounced structure-dependent thermal response, characterized by temperature-dependent heat capacity, non-uniform surface temperature distribution, and localized thermal inertia under external heating.

The most significant finding is that the thermal response cannot be described solely by homogeneous bulk material properties. Instead, the hierarchical organization of the wing strongly influences heat storage, transfer, and spatial temperature distribution, resulting in a structure-dependent apparent infrared response. This structure–property–response relationship represents the principal functional insight obtained from the investigated biological system.

These findings provide a basis for bioinspired thermal management concepts in which hierarchical surface architectures are designed to control heat redistribution and delay thermal equilibration. Such an approach may offer a potential route toward reducing infrared contrast under transient thermal conditions and developing passive materials for infrared signature management.

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