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Oleksandr Siora
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: siora@paton.kiev.ua
https://orcid.org/0009-0005-8542-1633

Volodymyr Lukashenko
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: z_lyk@ukr.net
https://orcid.org/0000-0002-9685-4654

Artemii Bernatskyi*
E. O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine
11, Kazymyra Malevycha Street, Kyiv, Ukraine, 03150
E-mail: bernatskyi@paton.kiev.ua
https://orcid.org/0000-0002-8050-5580

*(corresponding author)

An interdisciplinary study of the effect of laser radiation on carbon fiber-reinforced polymer, in the context of counteracting unmanned aerial vehicles

Abstract. *This article presents an interdisciplinary study that combines historical analysis and experimental research to explore the vulnerability of military drones made from carbon fiber-reinforced polymer to destruction by laser radiation. The work is structured around two interconnected areas: the historical evolution of carbon fiber-reinforced polymer use in military drone construction and the parallel development of high-energy laser systems as precision countermeasures. The historical section traces the trajectory of carbon fiber composites from their initial applications in aerospace and defense industries during the late 20th century to their widespread adoption in military unmanned aerial vehicles, driven by the need for lightweight, durable, and radar-evading materials. Special attention is given to geopolitical, technological, and* *strategic factors that influenced the increasing reliance on carbon fiber-reinforced polymer for enhancing drone performance in terms of range, payload, and survivability. In parallel, the article examines the emergence of directed energy weapons, focusing on laser systems, as a response to the limitations of conventional kinetic countermeasures in neutralizing fast, small, and low-observable drones. The study outlines how the military's growing concern with swarm attacks and stealth unmanned aerial vehicles has accelerated investments in laser-based air defense systems capable of engaging airborne targets with high accuracy and low operational cost. The experimental component investigates the mechanisms of laser-induced damage in carbon fiber-reinforced polymer materials through controlled laboratory tests, during which samples are exposed to varying intensities and durations of laser radiation. The results are analyzed to determine the energy thresholds and exposure conditions that lead to effective material destruction. By synthesizing historical and experimental data, the article provides a comprehensive understanding of how past material choices have shaped current vulnerabilities in drone technology and how modern laser systems are specifically adapted to exploit those weaknesses. This integrated approach not only bridges the gap between history and applied science but also contributes to the development of more effective and informed counter-drone strategies in contemporary and future military operations.*

Keywords: *unmanned aerial vehicle; Counter Unmanned Aircraft Systems (C-UAS); laser weapon; carbon fiber-reinforced polymer; destruction*

Introduction.

Plastics and plastic composites based on polymers like polyethylene, polypropylene, PVC, PET, and epoxy resins are widely used across modern life due to their strength, flexibility, and cost-efficiency. They are found in packaging, automotive parts, electronics, construction materials, textiles, and medical equipment (Demchenko et al., 2022; Masiuchok et al., 2022). Composites reinforced with glass or carbon fibers offer enhanced mechanical performance, making them essential in aerospace, sports, and defense industries (Nugraha et al., 2022). Their versatility and adaptability have made them integral to industrial and consumer products alike. However, their extensive use also raises concerns over environmental sustainability, recycling challenges, and long-term ecological impact.

Carbon fiber-reinforced polymer (CFRP), commonly known as carbon fiber, has become increasingly popular in the design and production of military drones due to its superior performance characteristics that align with the tactical, operational, and strategic demands of modern warfare (Björck, Svedbrand, Sjöqvist, & Edström, 2022). One of the most critical factors is its exceptional strength-to-weight ratio, which enables military drones to carry larger payloads, such as advanced sensors, surveillance equipment, electronic warfare systems, or guided munitions, while maintaining lower overall mass. This lightweight yet strong material allows for extended flight durations, greater operational ranges, and improved fuel efficiency or battery endurance – key parameters in reconnaissance, surveillance, and combat missions. Carbon fiber's low radar cross-section is another decisive advantage in military contexts, as its non-metallic composition can reduce the radar visibility of drones, making them more difficult to detect by enemy defense systems and enhancing their stealth capabilities. Unlike metallic materials, CFRP does not reflect radar waves in the same way, making it highly suitable for the development of low-observable UAVs used in intelligence-gathering and strike operations in contested airspace (Allheily et al., 2016). Additionally, the structural rigidity and vibration-damping qualities of carbon fiber are critical in ensuring stable imagery and reliable operation of precision targeting systems, particularly during high-speed maneuvers or turbulent weather conditions. The resilience of CFRP under mechanical stress and its resistance to corrosion and fatigue under repeated cycles of load and environmental exposure further increase the durability and survivability of drones in harsh battlefield environments (Schäffer et al., 2024). From desert heat and coastal humidity to cold mountain climates, military drones often operate under extreme and variable conditions where conventional materials might degrade or fail; CFRP maintains performance integrity across these scenarios, reducing maintenance needs and increasing operational readiness. The flexibility of carbon fiber manufacturing techniques – such as custom molding and composite layup – also allows engineers to produce complex aerodynamic shapes that optimize lift, reduce drag, and enhance maneuverability, giving military UAVs an edge in speed, agility, and evasion. Moreover, CFRP enables the integration of embedded systems and components within the structure itself, including wiring channels, sensor housings, and even antennas, facilitating compact and streamlined designs that lower profile and improve mission adaptability. As military drones become increasingly modular and multifunctional – capable of switching roles from surveillance to strike or electronic warfare – CFRP supports rapid prototyping and reconfiguration. Cost efficiency is another emerging factor; while carbon fiber was once considered prohibitively expensive, advances in manufacturing and economies of scale have brought down costs, making it more feasible for defense applications where the performance return outweighs the investment. Lastly, as militaries invest in drone swarms and expendable UAVs, carbon fiber offers a balance between robustness and economic viability, allowing for high-performance platforms that are cost-effective even when deployed in high-risk or single-use scenarios. Taken together, these factors explain why carbon fiber-reinforced polymer has become a foundational material in military drone development, supporting not just structural efficiency but also stealth, resilience, adaptability, and advanced mission capabilities.

Lasers are deeply integrated into modern technology, with material processing being one of their most widespread and transformative applications. In industrial settings, lasers are used for high-precision cutting, welding, drilling, and marking of metals, plastics, ceramics, and composites (Shelyagin et al., 2005; Korzhyk et al., 2022; Lesyk et al., 2024). Their ability to deliver concentrated energy with minimal thermal distortion makes them ideal for producing clean, accurate cuts and joints in automotive, aerospace, and electronics manufacturing. Laser welding is increasingly favored for its speed and strength, especially in battery production and lightweight component assembly (Kumar, Tomashchuk, Jouvard, & Duband, 2024). In microelectronics and semiconductor industries, lasers enable delicate micromachining, surface texturing, and patterning at sub-micron scales. Additive manufacturing processes like selective laser sintering (Goncharuk, Zhuk, Kaglyak, Dzhemelinskyi, & Lesyk, 2018; Zavdoveev et al., 2022; Sokolovskyi & Bernatskyi, 2023) and direct metal laser sintering are revolutionizing the production of complex parts, reducing material waste and accelerating prototyping. Lasers are also widely used for surface treatments, such as hardening, annealing, and coating removal, extending the lifespan and performance of components (Berdnikova et al., 2021; Kritskiy et al., 2022). Beyond manufacturing, lasers play key roles in telecommunications, medicine, environmental sensing, and consumer electronics. In the military sphere, lasers are being developed and deployed as directed energy weapons capable of neutralizing drones, missiles, and other threats with precision and speed. Additionally, they are used for range finding, target designation, and optical communication in modern combat systems, enhancing accuracy and operational capability.

The current stage of development of countermeasures and means of destruction targeting military drones made of CFRP reflects a rapidly evolving intersection of material science, directed energy weapons, kinetic interceptors, and electronic warfare systems designed specifically to overcome the advantages offered by carbon-based composite materials. Carbon fiber, with its high strength-to-weight ratio, resistance to corrosion, and low radar visibility, presents a unique challenge to traditional anti-aircraft systems, prompting the development of more specialized counter-drone technologies. One major focus area is the advancement of directed energy weapons, particularly high-energy lasers, which are proving effective against CFRP drones due to their ability to induce rapid localized heating (Yang et al., 2020; Nallamalli, Singh, & Kumar, 2023; Schäffer, Wolfrum, Lueck, & Osterholz, 2024). Despite carbon fiber's high tensile strength and thermal tolerance, it remains vulnerable to concentrated laser exposure, which can cause resin matrix decomposition, delamination, and eventual structural failure. As a result, militaries and defense contractors are fine-tuning targeting algorithms to maintain precise beam focus on critical drone components – such as rotor arms or control surfaces – for long enough to achieve functional incapacitation, even at standoff distances. Similarly, microwave-based weapons are being adapted to exploit the carbon composite structure’s potential weaknesses in shielding sensitive electronics; while CFRP is non-metallic and may not act as a conventional antenna, it often lacks the electromagnetic shielding capacity of metallic airframes, leaving embedded systems like GPS, flight controllers, and communication modules susceptible to directed electromagnetic pulses and high-powered microwave attacks. Concurrently, kinetic intercept systems are evolving to address the increased agility and reduced radar signature of carbon fiber drones. These include enhanced radar and infrared sensors capable of detecting low-observable

UAVs and guiding interceptor missiles or smart projectiles with improved terminal accuracy. Even conventional anti-aircraft guns are being upgraded with advanced fire control systems and proximity-fuzed ammunition to increase kill probability against fast, maneuverable, carbon-based drones. Another promising frontier involves drone-on-drone countermeasures, in which AI-guided interceptor UAVs physically ram or disable enemy drones mid-air, exploiting the lightweight, brittle nature of CFRP structures that are strong under tensile loads but vulnerable to concentrated mechanical impacts. At the same time, soft-kill approaches such as GPS spoofing, radio frequency jamming, and cyber intrusion continue to develop, taking advantage of the fact that, regardless of structural material, all drones rely on complex electronic systems to operate. While CFRP structures offer mechanical resilience, they provide no inherent defense against signal interference, making electronic warfare a highly effective, low-cost method to neutralize drones without requiring physical destruction. Research is also being directed toward material-specific sensors and tracking systems that can identify the distinct thermal or spectral signature of carbon fiber UAVs, which could support early warning and targeting for both defensive installations and mobile units. In parallel, the emergence of multi-layered drone defense systems – integrating radar, electro-optical sensors, electronic warfare suites, and rapid-response kinetic or laser weapons – is reshaping how militaries approach drone threats, particularly swarms of fast, low-flying UAVs constructed from CFRP (Björck, Svedbrand, Sjöqvist, & Edström, 2022; Taillandier et al., 2023; Schäffer et al., 2024).

Research Methods.

The methodology of this article is based on an interdisciplinary approach that integrates historical analysis with experimental studies to examine the development and destruction of military drones made of CFRP under laser radiation. The historical component involves a systematic study of the evolution of both CFRP materials in military aviation and the parallel development of directed energy weapons, with a focus on high-energy lasers (Bernatskyi, Lukashenko, Siora, & Sokolovskyi, 2024). Archival research will be conducted using military reports, defense industry publications, scientific journals, patent databases, and declassified documents to trace how and why CFRP became the preferred material in military drone construction, especially from the late Cold War period to the present. Particular attention will be paid to the influence of strategic doctrines, material science advancements, and the growing demand for stealth, agility, and endurance in unmanned aerial systems. In parallel, the study will analyze the military and technological motivations behind the development of laser weapons as a response to the increasing use of composite-material drones. The experimental part of the research will focus on the interaction between laser radiation and CFRP materials commonly used in drone manufacturing. Using controlled laboratory settings, CFRP samples will be exposed to high-energy laser beams under varying power levels, exposure times, and beam diameters. The results will help determine the thresholds at which laser radiation causes structural failure in carbon fiber composites. The integration of historical context with material testing will allow for a better understanding of how past choices in materials and military technology have shaped the current vulnerabilities and countermeasure strategies involving lasers. This combined methodology offers a dual lens – looking backward to trace the technological path that led to the current use of CFRP in drones, and looking forward to assess how laser-based systems exploit specific material weaknesses in modern warfare.

Results and Discussion.

Laser-Based Destruction of Military Drones Made from CFRP.

Laser-based destruction of military drones made from CFRP represents one of the most intensively researched frontiers in modern directed energy weapon (DEW) development (Figure 1), as militaries and defense agencies seek effective, precise, and scalable countermeasures to address the growing threat posed by stealthy, agile, and increasingly autonomous unmanned aerial systems (Schäffer et al., 2024).

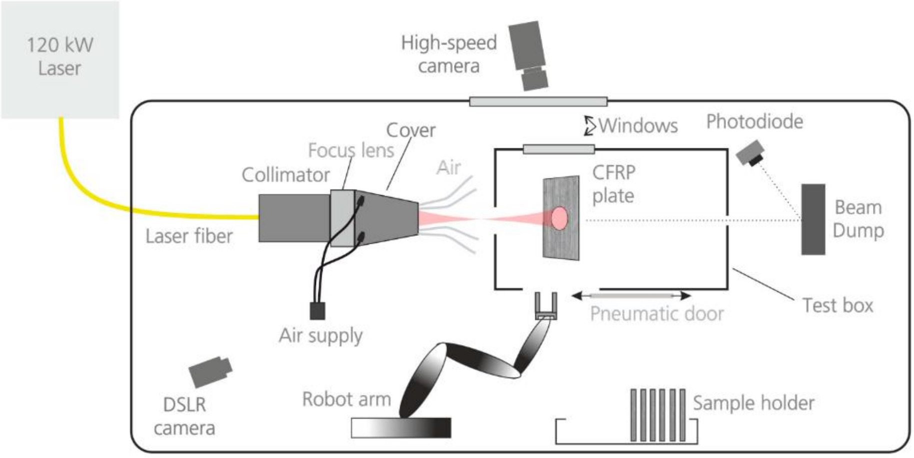


Figure 1. Experimental setup includes an automated sample exchange, operated by a robotic arm (Schäffer et al., 2024).

The interest i targeting CFRP drones with laser radiation arises from a unique intersection of the material properties of carbon composites and the operational characteristics of high-energy laser systems (Yang et al., 2020; Liao, Huang, & Xie, 2023; Taillandier, Regnault, Beaumadier, Beigbeder, & Pasquier, 2024). While CFRP is celebrated in drone design for its high strength-to-weight ratio, corrosion resistance, and reduced radar cross-section, it also possesses critical vulnerabilities – especially when exposed to sustained, high-intensity electromagnetic energy in the form of focused laser beams. Current research into laser-CFRP interactions is multifaceted (Figure 2), drawing from materials science, aerodynamics, optical engineering, thermomechanical modeling, and systems integration to determine optimal destruction strategies that can be deployed in real-world combat environments (Tresansky, Joyce, Radice, & Watkins, 2014; Taillandier et al., 2022).

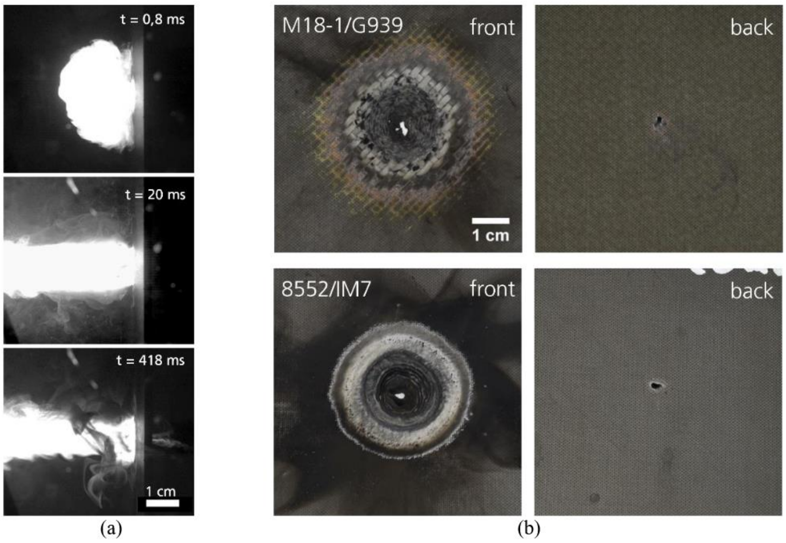
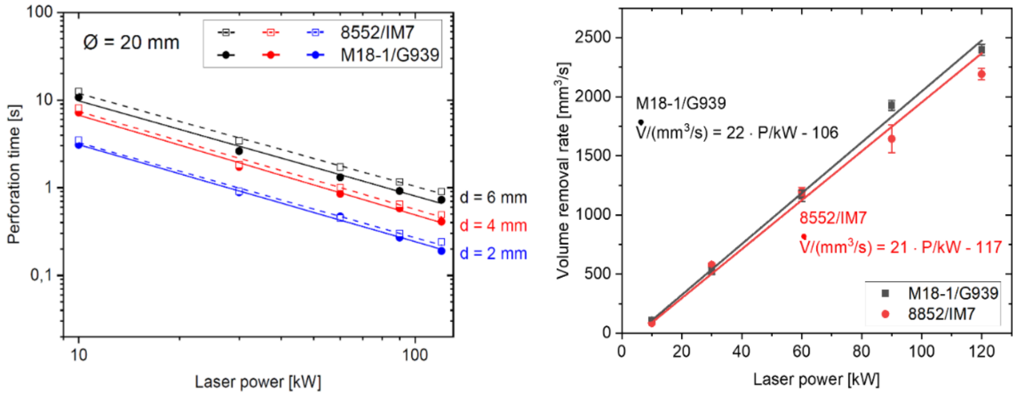


Figure 2. *(a)* Irradiation of CFRP with a laser power of 120 kW and a spot size of 20 mm results in an expanding gas cloud. The 4 mm thick CFRP plate is perforated after 0.4 seconds. *(b)* images of the damage zones on the front and back of irradiated CFRP samples made from two different fiber materials (Schäffer, Wolfrum, Lueck, & Osterholz, 2024).

One of the most fundamental aspects of this research is the study of thermal degradation mechanisms of CFRP under high-energy laser irradiation (Kujawinska, Kustron, Siedlecki, & Malesa, 2017; Schleijpen et al., 2020; Schäffer et al., 2024). Unlike metals, which typically melt under laser heating, CFRP materials undergo a more complex failure process due to their composite structure, which consists of carbon fibers embedded in a polymer matrix, usually an epoxy resin (Yang et al., 2020). When irradiated, the resin component absorbs laser energy and begins to thermally degrade at relatively low temperatures – around 300–400°C – causing delamination and decomposition, while the carbon fibers themselves can oxidize or structurally weaken at higher temperatures exceeding 600–1000°C. Researchers are investigating how different laser wavelengths, pulse durations, and power densities affect this failure sequence. For example, infrared lasers, particularly those in the 1.06–1.07 µm wavelength range (such as fiber lasers or Nd:YAG lasers), are often used due to their effectiveness in penetrating polymer layers and initiating thermal damage (Kim, Choi, & Kwon, 2024). Experiments have shown that with sufficient dwell time – i.e., the duration the laser beam remains fixed on a single point – CFRP components can be caused to structurally fail through a combination of matrix decomposition, fiber ablation, interlaminar cracking, and eventual rupture of load-bearing sections (Kujawinska, Kustron, Siedlecki, & Malesa, 2017).

In laboratory and field test environments, researchers are working to quantify the minimum energy thresholds required to defeat CFRP airframes under various atmospheric and operational conditions (see Figure 3). This includes accounting for heat diffusion in the material, the angle of incidence of the laser beam, and the rotation or movement of the target drone, which affects beam tracking and thermal coupling efficiency (Allheily et al., 2016; Zhang et al., 2018).



(a) (b)

Figure 3. *(a)* Perforation times as a function of laser power in a double-logarithmic representation for CFRP plate thicknesses of 2–6 mm and a beam diameter of 20 mm. *(b)* Volume removal rate as a function of laser power (Schäffer, Wolfrum, Lueck, & Osterholz, 2024).

For example, studies have shown that targeting thinner structural elements – such as rotor arms, wing spars, or propeller hubs – requires less laser energy than attempting to destroy denser, more reinforced areas such as the fuselage or payload housing. One notable focus is on beam control systems that can stabilize and focus the laser on a rapidly moving, small-scale target at long range (Björck, Svedbrand, Sjöqvist, & Edström, 2022). Adaptive optics, real-time tracking algorithms, and gimbaled beam directors are being refined to enable high-precision engagements even against drones flying at high speeds, performing evasive maneuvers, or operating under variable weather conditions (e.g., wind, dust, fog, or rain, all of which can scatter or absorb laser energy).

Simultaneously, materials scientists are conducting extensive microstructural analyses – using scanning electron microscopy, thermogravimetric analysis, and infrared spectroscopy – to observe how CFRP deteriorates at microscopic levels under laser exposure (Kujawinska, Kustron, Siedlecki, & Malesa, 2017; Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). These analyses provide insights into how the interfacial bonding between the carbon fibers and polymer matrix behaves under sudden, localized thermal stress. The role of composite layup orientation, resin type, fiber weave, and even manufacturing imperfections such as voids or air gaps is being examined to identify structural configurations that are either more vulnerable or more resistant to laser damage. This information is vital for military planning, as it can inform targeting strategies (e.g., where to aim the laser for quickest disablement) as well as counter-countermeasures (e.g., what drone designs might resist DEWs better).

In the article (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021) SEM images also show that within the direct radiation zone the fibers and the matrix are burned or chipped off and a coneshaped perforation has developed (Figure 4).

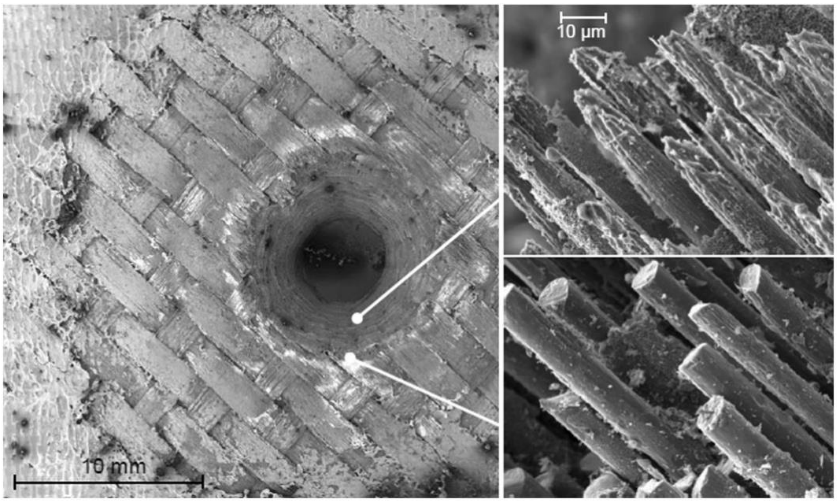


Figure 4. Scanning electron micrographs of a perforated 4 mm thick panel irradiated for 2.8 s (laser-spot-diameter: 10 mm; laser power: 5 kW), inserts show details inside and at the edge of the hole (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021).

Around the hole in the heat affected zone, the matrix has vanished on the front and back side of the panels, but the fibers are virtually undamaged (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). A closer look at the edge of the hole on the front side reveals a typical shape of broken fibers with residual matrix particles sticking on them. This observation suggests that by the sudden heating at the beginning of the irradiation the material is predominantly chipped off. Video recordings of the laser tests confirm that smoke forms notably at the beginning of the tests due to the sudden thermally induced stresses (Figure 5).

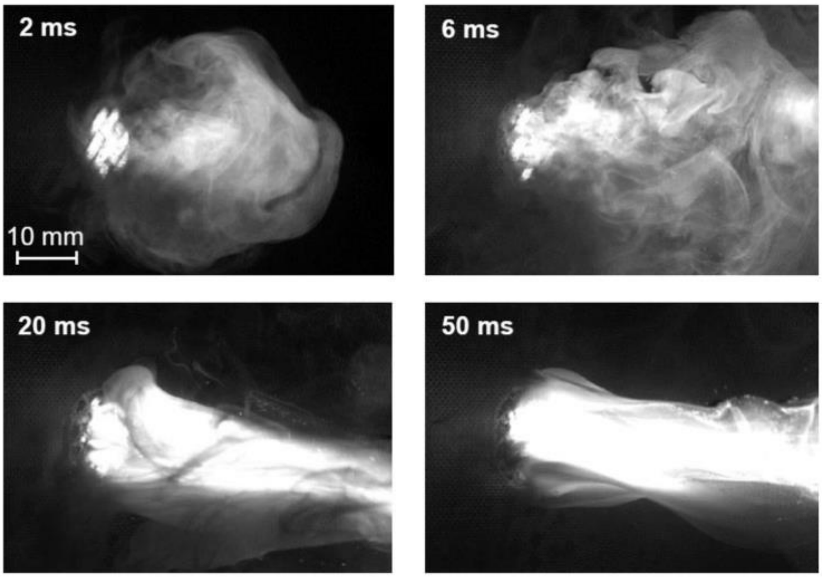


Figure 5. Images by a high-speed video camera showing different stages of the interaction of the high-power laser radiation with a 4 mm thick CFRP sample. (Laser power: 10 kW; Beam diameter: 10 mm; Perforation time: 1.2 s). (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021).

With increasing duration of the experiment, less chipping of fragments can be observed (Wolfrum, Eibl, Oeltjen, Osterholz, & Wickert, 2021). Then, oxidation processes additionally degrade matrix and fiber and less smoke forms. Inside the hole, the fibers look burned, the fiber ends are pointed and barely any matrix can be found on the fibers, both indicating that high temperatures have occurred. Additionally, the average carbon fiber diameter of initially 7.3±0.3 mm34 is reduced to 6.3±0.3 mm according to Figure 5 near the fiber ends and a rough surface structure of the fibers is observed. A decrease of the fiber diameter and the formation of surface defects are typical mechanisms of carbon fiber degradation in an oxidizing atmosphere. Thermal degradation of carbon fibers occurs beyond a minimum temperature of 650 °C in presence of oxygen, whereas the matrix degrades beyond ca. 300 °C within minutes. For the very short durations of the laser irradiation the temperatures are expected to be by far higher. A few small droplets probably are remains of melted glass fibers that are part of the M18-1/G939 material. In summary, the decomposition mechanism changes from chipping material to oxidizing it with increasing irradiation time and penetration depth. This finding specifies a report that theoxidative decomposition especially of carbon fibers does not occur, because formed pyrolysis products of the matrix hinders access of air. However, for prolonged laser treatment, ignition and oxidative decomposition occurr.

In parallel, computational modeling plays a major role in simulating laser-CFRP interactions (Tresansky, Joyce, Radice, & Watkins, 2014; Nan, Shen, Han, & Ni, 2019). Finite element models and computational fluid dynamics simulations are being used to predict heat transfer, material ablation, and structural failure modes under different laser exposure scenarios (see Figure 6).

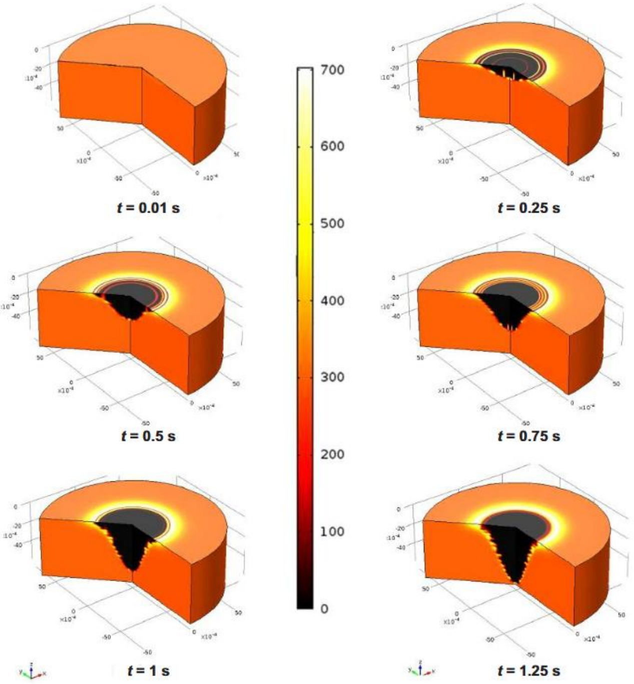


Figure 6. Computational modeling in simulating laser-CFRP interactions (Tresansky, Joyce, Radice, & Watkins, 2014).

These models are calibrated with experimental data and allow researchers to explore a vast range of variables – including different UAV geometries, composite thicknesses, and flight profiles – without the need for exhaustive physical testing. Such simulations are particularly important in military R&D contexts, where confidentiality, cost, and safety limit the scale of real-world trials. Moreover, these models are being integrated into software systems for use in operational laser weapon platforms, enabling real-time estimations of required dwell times and expected damage based on incoming drone specifications and environmental conditions (Nallamalli, Singh, & Kumar, 2023).

Another important area of research addresses the limitations of current laser systems against CFRP drones, particularly those designed for high-altitude or long-endurance missions (Björck, Svedbrand, Sjöqvist, & Edström, 2022). At high altitudes, for example, atmospheric density decreases, which can reduce laser absorption efficiency and beam coherence, thereby requiring more powerful or better-collimated lasers to maintain destructive energy densities. Additionally, some advanced drone designs incorporate ablative coatings or reflective surfaces to resist laser-induced damage, prompting counter-developments in multi-wavelength or pulsed laser systems capable of overcoming these defenses (Kujawinska, Kustron, Siedlecki, & Malesa, 2017). There is also growing attention to the thermal signature of drones during and after laser engagement; understanding how different CFRP configurations radiate heat can improve tracking and battle damage assessment capabilities, helping operators verify successful neutralization (Yang et al., 2020; Kim, Choi, & Kwon, 2024).

From a strategic perspective, militaries are increasingly viewing laser systems not just as tools for destruction, but as scalable platforms for layered defense against carbon-fiber-based UAVs. Low-power lasers may be used for disabling optical or infrared sensors, medium-power lasers for neutralizing propulsion systems or severing rotors, and high-power lasers for catastrophic structural failure (Allheily et al., 2016; Castrillo, Manco, Pascarella, & Gigante, 2022; Liao, Huang, & Xie, 2023). This layered approach aligns with the increasingly modular nature of both offensive drones and defensive energy weapons, allowing for tailored responses depending on the threat level, rules of engagement, or collateral risk. For example, in urban environments or near critical infrastructure, a precision laser strike that disables a CFRP drone without causing it to explode or crash uncontrollably may be preferable to kinetic interceptors or RF jamming techniques.

The current stage of applied research also includes extensive testing by defense agencies such as the U.S. Department of Defense, the Israeli Ministry of Defense, China's PLA, and NATO partners, all of whom are developing or deploying laser-based counter-UAV systems. Notable programs include the U.S. Army's DE M-SHORAD system, the U.S. Navy's LaWS (Laser Weapon System), Israel's Iron Beam, and Germany's HELWS initiative – all of which have demonstrated the ability to destroy or disable small drones made with composite materials, including CFRP. These systems aim for portability, rapid response times, and cost-efficiency per shot – since lasers operate using electrical power, they offer nearly unlimited "ammunition" compared to finite missile inventories. Such advantages are crucial as militaries confront increasingly frequent and diverse drone threats in asymmetric warfare scenarios.

Research into the destruction of CFRP-based military drones via laser radiation is in an advanced and fast-developing stage, with progress being made on multiple technical fronts – from materials science and beam control to targeting algorithms and thermal modeling (Tresansky, Joyce, Radice, & Watkins, 2014). While CFRP drones are formidable due to their lightweight durability and low observability, they are not impervious to well-targeted laser systems, especially when those systems are optimized for beam dwell, atmospheric correction, and material-specific engagement protocols (Björck, Svedbrand, Sjöqvist, & Edström, 2022). As laser technologies continue to mature and become integrated into mobile and fixed defense platforms, their role in neutralizing carbon-composite drones is set to expand significantly, reshaping the tactical landscape of drone warfare and accelerating the ongoing arms race between UAV innovation and counter-UAV lethality.

Experimental Study of the Effect of Laser Radiation on the CFRP & Discussion.

As part of the project "Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them", the authors identified the materials most commonly used to make parts of various UAVs. In particular, it was found that parts of the hull of attack UAVs can be made of CFRP. This research was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166 " Study of the effect of a laser beam on the materials of UAV parts and substantiation of the technical parameters of the laser equipment of the mobile complex to combat them".

This part of the article is devoted to the study of the behavior of carbon fiber-reinforced polymer plate under the action of high-power laser radiation to determine the optimal parameters of destruction of this composite material (see Figure 7).

Figure 7. Example of the obtained results of the study of the effect of laser radiation on the carbon fiber-reinforced polymer plate (Authors' source).

The use of laser weapons against unmanned aerial vehicles made of carbon fiber-reinforced polymer is an urgent task, so the study of the effect of laser beam parameters, such as power, spot diameter, and angle of incidence, on the material destruction efficiency is of great practical importance.

For the experiments, we used a Nd:YAG laser with a radiation power of up to 4.4 kW and a wavelength of 1.06 µm. Carbon fiber-reinforced polymer sheets with dimensions of 1000 × 500 × 2 mm were laser processed with the variation of such parameters as power (1-4 kW), beam diameter (5-20 mm), angles of incidence (30°, 45°, 60°, 90°), and laser beam travel speed (0.5-2 m/min). Figures 8–11 show the results of these studies as angle of incidence 90°.

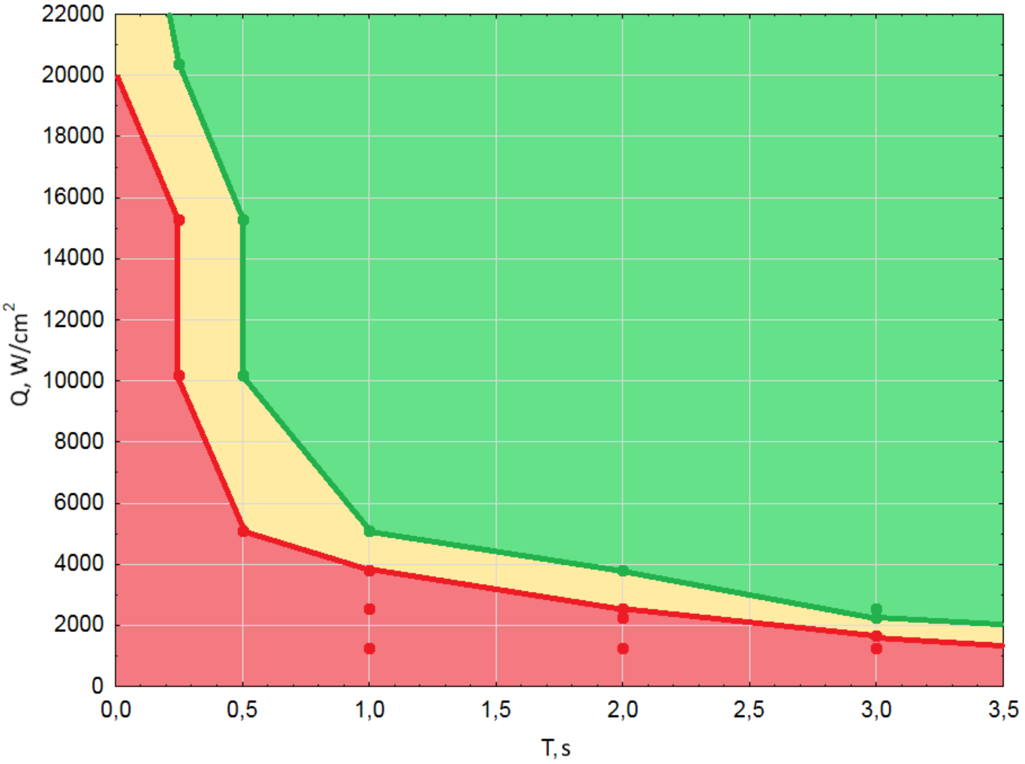


Figure 8. Graph of the effect of laser radiation on the penetration of a CFRP plate from power density as well as the exposure time.

The analysis of the data in this graph shows for penetration of a 2 mm thick CFRP plate, it is desirable to ensure a static exposure time of more than 0.5 s. The reason for this lies in the fact that during the laser treatment interval of 0.25-1 s, a 4x decrease in the laser power required to pierce the density is observed. It can also be noted that with an increase in the treatment time, the “uncertainty zone” (marked in yellow on the graph) decreases (see Figure 8).

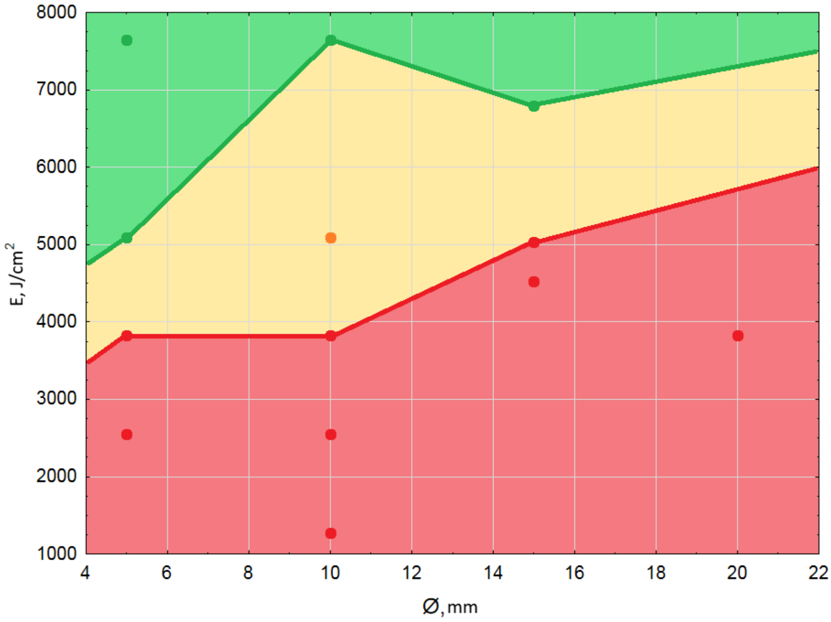


Figure 9. Diagram of the effect of laser radiation energy exposure and the diameter of the laser beam on the penetration of a CFRP plate.

The data shown in this graph indicate an increase in the energy exposure required to penetrate the carbon plate in proportion to the increase in the beam diameter (see Figure 9). This is attributed to a geometric increase in the beam cross-sectional area, which leads to a decrease in the laser power density. It is necessary to note the existence of an "uncertainty zone", in which cases with different processing results when using laser beams with identical energy exposure and beam diameter, exist due to the difference in the exposure time, which has a significant impact on the processing of this material.

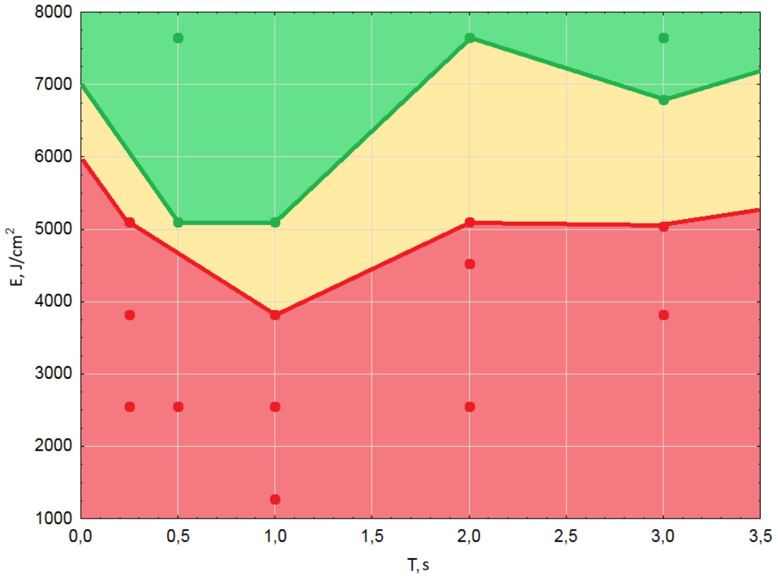


Figure 10. Diagram of the effect of laser radiation energy exposure and exposure time on the penetration of a CFRP plate.

The analysis of the data shown in Figure 10 shows that it is necessary to maintain the energy exposure at a level close to 5000 J/cm^2 to pierce a 2 mm thick CFRP plate. The anomaly, shown here is tied to the exposure time interval of 0.25–1 s, where the theoretically possible burn rate drops to 4000 J/cm^2. Despite this, this dependence holds for all other studied exposure time ranges.

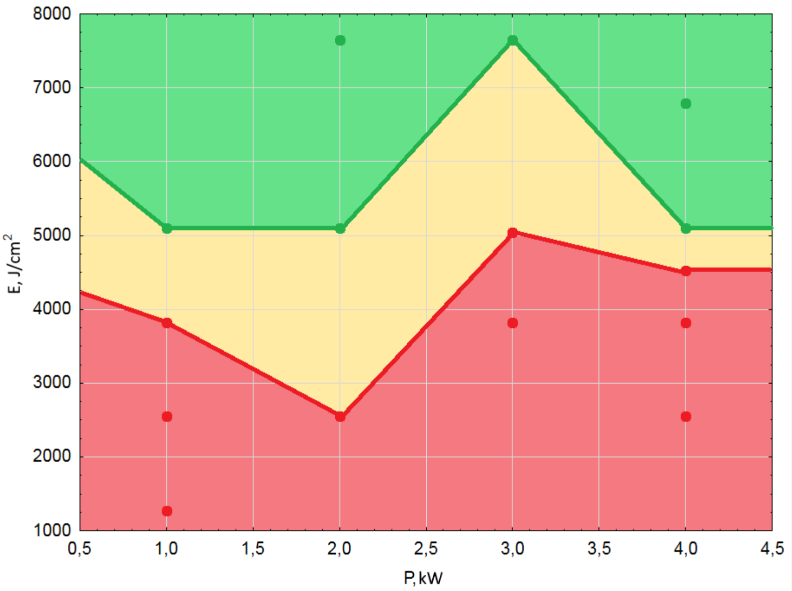


Figure 11. Diagram of the effect of laser radiation the energy exposure and laser power on the penetration of a CFRP plate.

This graph confirms the previously described principle, which states that in order to penetrate a plate of this material, it is necessary to ensure the energy component at a level above 5000 J/cm^2. A separate anomaly shown on this diagram is the guaranteed penetration point at 3 kW of laser power of 7644 J/cm^2, but the presence of an ‘uncertainty zone’ below this level is attributed to the lack of sufficient experimental data rather than an abnormal course of the penetration process at this laser power (see Figure 11).

The discussion of this interdisciplinary research reveals critical insights at the intersection of material science, military technology, and historical development, emphasizing how the strategic adoption of CFRP in drone design has created both technological advantages and new vulnerabilities – particularly in the face of modern laser weapon systems. Historically, the use of CFRP in military drones emerged in the late 20th century, initially within aerospace sectors such as the U.S. Department of Defense’s stealth programs (e.g., the Lockheed Martin RQ-170 Sentinel), where lightweight and radar-absorbing materials were essential for reconnaissance in contested airspace. This trend accelerated in the early 2000s with the proliferation of medium and small tactical drones (e.g., MQ-9 Reaper, Bayraktar TB2), many of which employed CFRP in structural elements such as wings, fuselages, and rotor blades to enhance endurance, payload efficiency, and low observability. The advantages of CFRP – such as high tensile strength-to-weight ratio and corrosion resistance – made it a logical material for long-range, reusable aerial systems. However, this research demonstrates that these same properties do not guarantee resilience under directed energy attack, especially laser radiation.

From a historical and strategic viewpoint, these data suggest that the evolution of drone material design – originally intended to maximize stealth and endurance – has unintentionally created a target profile highly susceptible to thermomechanical damage under precision laser fire. The study highlights the paradox in contemporary drone warfare: as military UAVs have become more advanced, autonomous, and difficult to detect, they have also become more structurally vulnerable to compact, high-energy laser systems that can disable them with minimal collateral damage and low per-shot cost. This duality is important for defense planners considering both procurement and counter-UAV strategies. While the historical embrace of CFRP reflected a rational response to the tactical needs of the late Cold War and post-9/11 periods (e.g., intelligence, surveillance, and reconnaissance dominance, strike capabilities, and endurance), the present research implies that survivability in the age of directed energy weapons may require rethinking UAV material systems or incorporating additional shielding, modular repair features, or laser-deflective coatings. In conclusion, the interdisciplinary approach – drawing on historical context and laboratory experimentation – provides a deeper understanding of the vulnerabilities embedded in current drone design philosophy and underscores the need for next-generation solutions in both drone resilience and countermeasure sophistication.

Conclusions.

The integration of historical analysis and experimental investigation has proven to be an effective methodology for examining both the development and destruction of military drones made from CFRP when exposed to laser radiation.

Historical research reveals that the rise of CFRP as a dominant material in military drone construction was driven by a convergence of strategic doctrines, material science innovations, and increasing operational demands for stealth, endurance, and agility, particularly from the late Cold War era onward. The adoption of CFRP was not merely a technical preference but a strategic decision influenced by military needs for radar-evading platforms and reduced weight without compromising structural integrity.

The parallel development of high-energy laser systems was driven by the limitations of conventional kinetic weapons in countering modern drones. Lasers emerged as a precise and cost-effective solution to the challenges posed by fast, maneuverable, and low-observable UAVs constructed from composite materials.

Laboratory tests was funded by the National Research Foundation of Ukraine under the project No. 2023.04/0166, demonstrated that CFRP is vulnerable to laser radiation under specific power levels, durations, and beam profiles. These results establish critical thresholds for structural degradation and confirm that CFRP drones can be neutralized effectively with well-calibrated laser systems.

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Conflicts of interest.

The authors declare no conflict of interest.

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Олександр Сіора
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Володимир Лукашенко
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Артемій Бернацький
Інститут електрозварювання ім. Є. О. Патона Національної академії наук України, Україна

Міждисциплінарне дослідження впливу лазерного випромінювання на полімер армований вуглецевим волокном, в контексті протидії безпілотним літальним апаратам

Анотація. *Ця стаття представляє міждисциплінарне дослідження, яке поєднує історичний аналіз та експериментальні дослідження для вивчення вразливості військових дронів, виготовлених з полімеру, армованого вуглецевим волокном, до руйнування лазерним випромінюванням. Робота структурована навколо двох взаємопов'язаних областей: історичної еволюції використання полімеру, армованого вуглецевим волокном, у будівництві військових дронів та паралельного розвитку високоенергетичних лазерних систем як високоточних контрзаходів. В історичному розділі простежується траєкторія розвитку композитів з вуглецевого волокна від їх початкового застосування в аерокосмічній та оборонній промисловості наприкінці 20 століття до їх широкого впровадження у військових безпілотних літальних апаратах, що було зумовлено потребою в легких, міцних та радіолокаційно-ізолюючих матеріалах. Особлива увага приділяється геополітичним, технологічним та стратегічним факторам, які вплинули на зростаючу залежність від полімеру, армованого вуглецевим волокном, для підвищення продуктивності дронів з точки зору дальності польоту, корисного навантаження та живучості. Паралельно у статті розглядається поява зброї спрямованої енергії, зосереджуючись на лазерних системах, як відповідь на обмеження звичайних кінетичних контрзаходів у нейтралізації швидких, малих та малопомітних дронів. У дослідженні окреслюється, як зростаюча стурбованість військових щодо ройових атак та малопомітних безпілотних літальних апаратів прискорила інвестиції в лазерні системи протиповітряної оборони, здатні вражати повітряні цілі з високою точністю та низькими експлуатаційними витратами. Експериментальний компонент досліджує механізми лазерного пошкодження в полімерних матеріалах, армованих вуглецевим волокном, за допомогою контрольованих лабораторних випробувань, під час яких зразки піддаються впливу лазерного випромінювання різної інтенсивності та тривалості. Результати аналізуються для визначення енергетичних порогів та умов впливу, що призводять до ефективного руйнування матеріалу. Синтезуючи історичні та експериментальні дані, стаття забезпечує всебічне розуміння того, як минулий вибір матеріалів сформував сучасні вразливості в технології дронів та як сучасні лазерні системи спеціально адаптовані для використання цих слабких місць. Цей інтегрований підхід не лише усуває розрив між історією та прикладною наукою, але й сприяє розробці більш ефективних та обґрунтованих стратегій боротьби з дронами в сучасних та майбутніх військових операціях.*

Ключові слова: *безпілотний літальний апарат; системи протидії безпілотним літальних апаратам (C-UAS); лазерна зброя; полімер армований вуглецевим волокном; деструкція*

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