CHAPTER «ENGINEERING SCIENCES»

EFFECTS OF HIGH-POWER LASER RADIATION ON FIBERGLASS COMPOSITE

Artemii Bernatskyi[1]

DOI: https://doi.org/10.30525/978-9934-26-602-7-5

Abstract. The presented chapter of monograph is devoted to the study of the role of glass-based composite plastics, in particular FR-4 fiberglass composite, in the design of modern unmanned aerial vehicles (UAVs) and to the investigation of their degradation mechanisms under the influence of laser radiation in the context of counter-UAV warfare. Over the past decade, the use of UAVs has grown exponentially, driven by their increasing affordability, versatility, and combat effectiveness. This trend has been vividly demonstrated during Russia's full-scale war against Ukraine, where small, low-cost drones have become central to reconnaissance, artillery fire adjustment, and direct strike missions. The large-scale and relatively unsophisticated production of UAVs has placed emphasis on inexpensive, readily available materials such as FR-4 fiberglass composite, which combines good mechanical strength, low weight, and electrical insulating properties. However, the widespread reliance on this material has simultaneously created new vulnerabilities that can be exploited by emerging directed energy weapons, particularly high-power lasers. *The purpose.* The primary purpose of this research is to investigate the mechanisms of degradation and destruction of glass-based composite plastics, specifically FR-4 fiberglass composite, under the influence of high-power laser radiation, with a focus on its application in counter-UAV warfare. The study aims to determine the critical laser parameters – including power, beam incidence angle, exposure time, and spot diameter – that result in irreversible structural damage or complete penetration of FR-4 components

[1] Candidate of Technical Sciences, Senior Researcher,
Head of the Department № 77 «Specialized high-voltage equipment and laser welding»,
E.O. Paton Electric Welding Institute of the National Academy of Sciences of Ukraine, Ukraine

used in UAV airframes and electronic systems. By combining a systematic review of existing literature with controlled experimental testing, the research seeks to provide a scientific basis for optimizing laser weapon engagement strategies and to identify the fundamental vulnerabilities of FR-4-based UAV designs, thereby contributing to the development of more effective counter-UAV technologies. *Methodology.* The research was carried out in two complementary stages. In the first stage, a comprehensive review of publicly available literature was conducted to analyze current trends in UAV construction, the increasing use of FR-4 as a structural and electronic material, and the known theoretical models describing laser–material interactions. This review provided the scientific foundation for identifying key parameters influencing FR-4 vulnerability to directed energy weapons. The second stage consisted of a controlled experimental investigation designed to determine the specific conditions under which laser radiation causes critical damage to FR-4 components. The experiments were performed using a fiber laser "MAX MFSC-6000M" (Maxphotonics, China) with a maximum output power of 6.0 kW and a radiation wavelength of λ = 1070 nm. Key process parameters were systematically varied: laser power levels of 1.0 kW, 2.0 kW, and 3.0 kW; beam incidence angles relative to the surface of 30°, 45°, 60°, and 90°; exposure durations of 0.25 s, 0.5 s, 1.0 s, 2.0 s, and 3.0 s; and beam spot diameters of 5.0 mm, 10.0 mm, 15.0 mm, and 20.0 mm. The tests were conducted on FR-4 fiberglass composite samples with a thickness of 2.0 mm, representing typical materials used in UAV airframes and circuit board substrates. *Results.* The experimental results demonstrated that exposure time is the dominant factor in determining laser effectiveness. It was found that for piercing 2.0 mm thick FR-4 sheets, the exposure time must exceed 0.5 s. Even at relatively low power densities (approximately 1000 W/cm^2) and with large beam diameters (15–20 mm), irradiation beyond this threshold reliably produced full penetration of the material. These findings confirm that FR-4 structures are highly vulnerable to sustained laser attacks, emphasizing the practicality of using laser weapons to neutralize UAVs constructed with this material. *Practical implications.* The study's practical implications are twofold. For the developers of laser-based counter-UAV systems, the results provide critical data for optimizing engagement parameters such as dwell time, focus, and targeting strategies. For UAV designers, the

research highlights the inherent vulnerabilities of FR-4 and points toward potential mitigation strategies, albeit with significant cost and weight trade-offs. *Value/originality.* The originality of this work lies in its integration of theoretical analysis with empirical experimentation, offering a rare, data-driven perspective on how high-power lasers interact with FR-4 composites. This study thereby contributes to both the advancement of directed energy weapon systems and the broader understanding of material survivability in modern aerial warfare.

1. Introduction

In recent years, the design of unmanned aerial vehicles (UAVs) has undergone a profound transformation, driven by rapid technological advances and the growing role of UAVs in modern warfare. The full-scale Russian invasion of Ukraine in 2022 has become a defining moment in this evolution, serving both as a catalyst for innovation and a testing ground for emerging concepts [1]. This conflict demonstrated that UAVs are no longer auxiliary assets but central elements of combat operations, capable of influencing the strategic balance on the battlefield.

One of the most notable trends is the widespread shift toward cost-effective, mass-produced UAVs that can be deployed in large numbers [2]. Early generations of military drones were often expensive, with complex avionics and composite structures, limiting their availability to well-funded militaries. However, the war in Ukraine has highlighted the effectiveness of low-cost commercial platforms that can be easily adapted for reconnaissance or strike missions. Small quadcopters and fixed-wing drones, sometimes costing only a few hundred dollars, have been modified to carry improvised explosive devices or to provide real-time targeting data. This has encouraged designers to prioritize simplicity and rapid production techniques, including 3D printing and the use of readily available civilian components [3].

Simultaneously, the conflict has accelerated the development of loitering munitions, or “kamikaze drones,” which combine the functions of a UAV and a guided weapon. These systems, ranging from sophisticated designs like the Russian Lancet series to improvised variants assembled by Ukrainian engineers, have proven highly effective against artillery, armored vehicles, and even air defense systems [2]. The success of such platforms has prompted a reevaluation of traditional missile and artillery doctrines, as UAVs offer greater flexibility and precision at a fraction of the cost of conventional weaponry.

Another significant trend is the increasing emphasis on electronic warfare resilience. The Ukrainian battlefield has been characterized by a dense electronic environment, with both sides deploying advanced jamming and signal interception technologies. As a result, UAV designers are focusing on improving autonomous navigation capabilities, secure communications, and anti-jamming measures. Artificial intelligence has begun to play a larger role, enabling drones to operate in GPS-denied environments, recognize targets independently, and coordinate swarm attacks without direct operator control. Swarming concepts, long discussed in theoretical studies, are now moving toward practical implementation, as militaries seek to overwhelm enemy defenses through coordinated mass UAV assaults.

Material science has also seen rapid progress, with new composite structures and lightweight alloys being introduced to enhance UAV endurance and survivability [4]. There is a growing interest in radar-absorbing coatings and low-visibility designs, aimed at reducing the detectability of drones by enemy sensors. At the same time, the availability of commercial materials has led to a dual trend: while some UAVs are becoming more sophisticated and stealthy, others rely on cheap, easily replaceable parts, reflecting a “high-low mix” strategy similar to that historically used in manned aircraft development.

Overall, the war in Ukraine has demonstrated that UAV design is entering a period of intense diversification. From advanced strike drones to disposable reconnaissance platforms, the spectrum of UAVs is expanding rapidly. These developments are reshaping military doctrines worldwide and setting the stage for a future in which unmanned systems play a decisive role not only in localized conflicts but also in the broader balance of global power.

The primary purpose of this research is to investigate the mechanisms of degradation and destruction of glass-based composite plastics, specifically FR-4 fiberglass composite, under the influence of high-power laser radiation, with a focus on its application in counter-UAV warfare. The study aims to determine the critical laser parameters – including power, beam incidence angle, exposure time, and spot diameter – that result in irreversible structural damage or complete penetration of FR-4 components used in UAV airframes and electronic systems. By combining a systematic review of existing literature with controlled experimental testing, the research seeks to provide a scientific basis for optimizing laser weapon engagement strategies and to identify the fundamental vulnerabilities of FR-4-based UAV designs, thereby contributing to the development of more effective counter-UAV technologies.

2. The role of glass-based composite plastics in UAV structures

The rapid evolution of UAVs over the past two decades has been closely linked to advances in materials science [5–7]. In the early stages of UAV development, designers primarily relied on traditional materials such as aluminum alloys and wood, which provided a balance between weight, cost, and manufacturability. However, as UAV designs became more complex and their operational roles expanded, the limitations of these conventional materials became increasingly apparent. Aerial platforms required lightweight yet strong structures capable of withstanding aerodynamic loads, vibrations, and harsh environmental conditions, while also being suitable for mass production at relatively low cost. This necessity led to the growing adoption of composite materials, including those based on carbon fibers, aramid fibers, and glass fibers.

Among these, glass-based composite plastics have emerged as a particularly attractive option, especially for small- and medium-sized UAVs [5]. Unlike carbon composites, which offer exceptional strength and stiffness but are relatively expensive and brittle, glass fiber composites provide a favorable balance of mechanical performance, cost-efficiency, and ease of processing. The most commonly used type of glass-reinforced plastic in UAV construction is FR-4 fiberglass composite, a material initially developed for the electronics industry as a substrate for printed circuit boards [8–10]. Over time, its favorable combination of mechanical, thermal, and dielectric properties has enabled its application in structural components of UAVs, particularly in airframes, control surfaces, and housings for electronic modules.

The use of glass-reinforced plastics in UAVs dates back to the mid-20th century, coinciding with the rise of synthetic polymers and the aerospace industry's search for new lightweight materials [4]. Early military drones, such as target drones and reconnaissance platforms developed during the Cold War, incorporated glass fiber laminates primarily in non-load-bearing components, including radomes and fairings [9]. However, as manufacturing techniques improved and the understanding of composite behavior deepened, designers began to employ glass fiber structures more extensively, extending their use to fuselage shells, wing spars, and internal frames. The turn of the 21st century marked a critical point, with UAV proliferation across both military and civilian domains creating unprecedented demand for low-cost yet reliable materials [11]. In this context, FR-4 emerged as a material that could bridge the gap between advanced aerospace-grade composites and inexpensive, low-performance plastics.

FR-4 is a composite laminate material consisting of woven glass fiber cloth impregnated with an epoxy resin binder. The designation "FR" stands for "flame retardant," reflecting one of the material's key attributes [12–14]. The woven glass fibers provide the structural backbone, imparting strength, stiffness, and dimensional stability, while the epoxy resin matrix distributes loads across the fibers and protects them from environmental damage. The resulting material exhibits a high strength-to-weight ratio, moderate flexibility, and excellent resistance to moisture, heat, and many chemical agents. From a mechanical standpoint, FR-4 is characterized by a tensile strength in the range of 300–500 MPa and a flexural strength typically exceeding 400 MPa, depending on fiber orientation and laminate thickness. Its density, around 1.85–1.90 g/cm^3, is higher than that of carbon fiber composites (approximately 1.55–1.60 g/cm^3) but significantly lower than aluminum alloys, which generally range from 2.65 to 2.80 g/cm^3. This makes FR-4 particularly attractive for small UAVs, where weight savings are critical but extreme performance is not always required. Additionally, its fatigue resistance is superior to many metals, a vital consideration for UAV components exposed to cyclic aerodynamic loads during extended flight operations.

Thermal stability is another important property of FR-4 [13; 14]. Typical glass transition temperatures (Tg) range from 130°C to 180°C, depending on the specific formulation. This allows the material to withstand the thermal stresses encountered in UAV operation, such as those caused by frictional heating, sun exposure, or localized heat sources like electric motors and avionics. Furthermore, FR-4's low dielectric constant and excellent electrical insulation characteristics make it ideal for integrating electronic subsystems directly into structural components. This dual functionality has given rise to the concept of structural electronics, where UAV designers embed sensors, antennas, and power distribution circuits directly into FR-4-based airframe sections.

The advantages of FR-4 fiberglass composite in UAV design are multifaceted. Perhaps the most significant is its cost-effectiveness [15]. While advanced aerospace composites such as carbon fiber reinforced polymers offer superior mechanical performance, their production costs remain high due to the complexity of fiber fabrication, layup processes, and curing cycles. FR-4, by contrast, benefits from decades of mass production for the electronics industry, resulting in a mature and highly optimized supply chain. This allows UAV manufacturers to source high-quality composite sheets at relatively low prices, reducing overall production costs and enabling the deployment of large UAV fleets.

Another key advantage is manufacturing versatility [16]. FR-4 can be easily cut, drilled, and machined using conventional tools, facilitating rapid prototyping and field repairs. Its thermosetting epoxy matrix allows for various forming techniques, including compression molding and vacuum-assisted resin transfer molding, which are compatible with both small-scale workshops and industrial production lines. This flexibility has proven particularly valuable in the context of wartime innovation, as seen during the ongoing Russian-Ukrainian war. Ukrainian engineers and volunteer groups have leveraged FR-4 and similar materials to produce improvised UAV components, taking advantage of its availability and ease of processing under resource-constrained conditions.

Additionally, the material's impact resistance and damage tolerance are critical attributes in combat environments. Unlike brittle carbon fiber composites, which tend to fail catastrophically upon impact, glass fiber laminates exhibit more gradual failure modes, absorbing energy through fiber breakage and delamination. This makes UAVs constructed with FR-4 more resilient to rough handling, hard landings, and minor combat damage. Such robustness is particularly important for reconnaissance and loitering drones operating at low altitudes, where collisions with vegetation, structures, or debris are common.

From an operational perspective, FR-4's compatibility with electronic systems is another decisive factor. Many UAVs, especially those used for surveillance, rely on complex sensor suites, communications equipment, and guidance systems. By using FR-4 for both structural and electronic components, designers can streamline assembly processes, reduce electromagnetic interference, and minimize the overall weight of the platform. For instance, a UAV wing made from FR-4 laminates can incorporate embedded antenna elements without the need for separate housings, thereby improving aerodynamic efficiency and simplifying maintenance.

FR-4's role in UAV construction spans a wide range of components [17]. In small quadcopters and fixed-wing UAVs, it is commonly used for fuselage panels, internal frames, and motor mounts, where moderate strength and dimensional stability are required. Its resistance to warping and moisture absorption ensures that these critical components maintain their shape and functionality even under fluctuating environmental conditions.

In medium-sized UAVs, FR-4 often serves as the material for wing spars and control surface skins, where it must resist bending and torsional loads during maneuvers. Designers frequently employ hybrid constructions, combining FR-4 with lightweight foam cores or carbon fiber reinforcements to optimize performance. For example, a typical UAV wing might feature an FR-4 outer skin bonded to an internal honeycomb structure, providing a balance between strength, stiffness, and weight reduction.

Another notable application is in protective housings for avionics and payload systems. FR-4's flame-retardant properties and electrical insulation make it ideal for enclosing sensitive electronics, protecting them from electromagnetic interference and mechanical shock. In combat UAVs, these housings often double as armor against small arms fire and shrapnel, exploiting the material's energy-absorbing characteristics.

One of the key reasons for the popularity of FR-4 in UAV construction is its ability to withstand diverse environmental conditions. UAVs are routinely exposed to temperature fluctuations, moisture, ultraviolet (UV) radiation, and chemical contaminants, all of which can degrade materials over time. FR-4 demonstrates excellent resistance to moisture absorption, with typical water uptake values below 0.15%. This property ensures that UAV components maintain dimensional stability even when operated in humid or rainy environments. For fixed-wing UAVs that must maintain precise aerodynamic profiles, this resistance to warping is particularly critical.

Despite its many advantages, FR-4 fiberglass composite is not without drawbacks [18-20]. One of the most significant limitations is its relatively high density compared to advanced aerospace composites. While its density of 1.85–1.90 g/cm³ is lower than aluminum, it remains substantially higher than that of carbon fiber composites, which typically range from 1.55 to 1.60 g/cm³. This difference becomes critical in larger UAVs, where weight savings translate directly into increased payload capacity and range. Consequently, high-performance UAV designs often reserve FR-4 for secondary structures while relying on carbon composites for primary load-bearing elements. Another challenge lies in the material's limited stiffness-to-weight ratio. While FR-4 offers sufficient rigidity for small UAVs, its modulus of elasticity is lower than that of carbon fiber, leading to greater deflections under load. This can affect the aerodynamic precision of wings and control surfaces, particularly in high-speed UAVs or those operating under heavy payload conditions. To address this, designers frequently employ hybrid laminates, combining FR-4 with stiffer fibers in critical regions. Such solutions, while effective, increase manufacturing complexity and cost.

The behavior of FR-4 under high-energy impacts also poses challenges. Although the material exhibits gradual failure modes, making it more forgiving than brittle carbon composites, it is still susceptible to delamination and fiber pull-out under severe loads. In military applications, where UAVs may encounter shrapnel or small-caliber fire, this vulnerability can lead to rapid degradation of structural integrity. Research efforts are ongoing to improve the toughness of glass fiber composites through advanced resin formulations and innovative layup techniques.

The widespread use of FR-4 in UAVs has significant implications for modern military strategy. The Russian-Ukrainian war has highlighted the transformative potential of low-cost drones, many of which rely on FR-4 structures. By enabling the rapid and inexpensive production of UAVs, this material has contributed to a shift in the balance of power on the battlefield. Small tactical units can now deploy their own aerial reconnaissance and strike assets without relying on centralized command structures, increasing operational flexibility and decentralization.

This democratization of air power has forced militaries worldwide to reconsider their force structures and doctrines. Traditional air defense systems, designed to counter high-value aircraft and missiles, are often ill-suited to deal with swarms of inexpensive drones. As a result, new counter-UAV technologies are being developed, including directed energy weapons, electronic warfare systems, and specialized kinetic interceptors. The proliferation of FR-4-based UAVs has thus created a parallel arms race, with defense industries seeking to balance offense and defense in this new domain.

The lessons learned from Ukraine are already influencing procurement decisions in NATO countries and beyond. Several European defense manufacturers have announced plans to establish production lines for low-cost UAVs that explicitly incorporate FR-4 and similar materials. These initiatives aim to create stockpiles of expendable drones that can be deployed in large numbers during future conflicts. In this context, FR-4 serves not merely as a material choice but as a strategic enabler, shaping the tactics and economics of modern warfare.

3. The effect of laser radiation on the degradation of glass-based composite plastics in counter-UAV warfare

The rapid proliferation of UAVs in both civilian and military domains has fundamentally reshaped the technological landscape of modern conflict. In particular, the Russian-Ukrainian war has demonstrated the decisive role of small, low-cost UAVs in reconnaissance, target acquisition, and strike missions. These drones often rely on composite materials for their airframes, including carbon fiber reinforced polymers, aramid composites, and glass-based plastics such as fiberglass laminates. Among these, FR-4 fiberglass composite, traditionally used in the electronics industry, has become especially widespread due to its low cost, availability, and favorable mechanical and electrical properties. The material serves not only as a structural component in UAV airframes but also as the substrate for printed circuit boards and integrated avionics. Consequently, understanding the effects of directed energy weapons, particularly high-energy lasers, on FR-4 and similar composites has emerged as a critical area of research in the development of counter-UAV technologies [4].

Laser weapons are increasingly viewed as an attractive solution for neutralizing hostile drones [21–23]. Unlike conventional kinetic interceptors, laser systems offer virtually instantaneous target engagement, low cost per shot, and deep magazines limited only by the power source. For lightweight UAVs, even modest levels of laser energy can cause mission-killing damage by degrading structural components or disabling electronic subsystems. However, the precise mechanisms by which laser radiation interacts with composite materials are complex and depend on a wide range of factors, including the laser wavelength, power density, pulse duration, and the optical and thermal properties of the target material. In the case of FR-4 fiberglass composite, these interactions involve a combination of thermal, photochemical, and mechanical processes that ultimately lead to material degradation and failure.

FR-4 is a glass-reinforced epoxy laminate, consisting of woven glass fiber cloth embedded in a thermoset epoxy resin matrix. The glass fibers, typically composed of silica-based formulations, provide the bulk of the material's mechanical strength, while the epoxy serves as a binding medium that transfers loads between fibers and protects them from environmental damage. This heterogeneous structure introduces anisotropic behavior when exposed to laser radiation. The glass fibers have relatively high thermal stability, with melting points in excess of 1000°C, and exhibit limited absorption of infrared wavelengths commonly used in laser systems [13; 24; 25]. In contrast, the epoxy matrix has a much lower thermal degradation threshold, typically beginning to decompose at temperatures around 250–350°C. As a result, when a laser beam strikes FR-4, the initial interaction is dominated by the rapid heating and breakdown of the polymeric phase rather than the glass fibers.

The epoxy's optical properties also play a critical role. Most epoxies used in FR-4 are relatively opaque to high-energy laser wavelengths such as 1064 nm (Nd:YAG lasers) and 10.6 μm (CO_2 lasers) [4; 21; 26]. This opacity leads to surface absorption of the laser energy, resulting in intense localized heating. The presence of flame-retardant additives, which give FR-4 its designation, can modify this interaction by releasing halogenated compounds during decomposition. These compounds may form transient plasmas or soot layers that either absorb additional energy or reflect part of the incoming beam, complicating the energy transfer process. In practical terms, this means that laser engagement of FR-4 structures often exhibits nonlinear behavior, with periods of rapid ablation interspersed with brief intervals of reduced damage as protective byproducts form and dissipate.

The woven structure of the glass fibers introduces further complexity. As the epoxy begins to degrade, voids form around the fibers, creating localized regions of differential heating. The fibers themselves can act as thermal conduits, redistributing heat within the material and potentially causing subsurface damage away from the point of laser impact. This phenomenon is particularly significant in UAV airframes, where thin FR-4 panels may delaminate or blister even when the surface appears only mildly charred. Such hidden damage poses challenges for assessing UAV survivability and for developing effective counter-UAV tactics.

The effectiveness of laser weapons against FR-4-based UAVs depends not only on the material properties but also on the operational context. In real-world combat scenarios, factors such as target range, relative motion, atmospheric conditions, and UAV design must all be considered. Small quadcopters and fixed-wing drones often present low radar and infrared signatures, making them difficult to track and target. However, once locked on, their lightweight FR-4 structures are highly vulnerable to even brief laser exposures.

Experimental data from field tests and combat reports suggest that a continuous-wave laser with a power output of 30–50 kW can disable most small UAVs within 2–5 seconds of focused irradiation [27–29]. The initial damage typically manifests as localized charring of the epoxy, followed by rapid structural weakening and loss of flight stability. In some cases, particularly with loitering munitions designed for single-use missions, the onboard explosive payload may detonate if heated by the laser, achieving complete neutralization. However, this outcome also presents risks to nearby friendly forces, emphasizing the need for precise control of laser engagement parameters.

Atmospheric effects such as aerosol scattering, turbulence, and humidity can significantly reduce the effective power delivered to the target. Smoke, fog, or battlefield dust may absorb or deflect the laser beam, requiring higher initial power or longer dwell times. FR-4's surface condition further influences energy absorption. UAVs with dark, matte coatings absorb laser energy more efficiently than those with reflective or glossy surfaces.

Some combatants have experimented with applying reflective films or ceramic coatings to drone surfaces as a form of improvised laser countermeasure. While such measures can delay the onset of damage, they cannot fully protect FR-4 structures due to the fundamental mismatch between the material's thermal limits and the concentrated energy of high-power lasers.

An additional operational factor is the placement of critical components within the UAV. Because FR-4 serves both structural and electronic roles, a laser strike that penetrates the airframe may simultaneously damage avionics housed on FR-4 circuit boards. This dual vulnerability increases the likelihood of mission-kill outcomes even if the UAV remains physically intact. For instance, disabling the flight controller through localized heating can cause immediate loss of control, forcing the drone to crash.

The study of laser interactions with FR-4 fiberglass composite has direct implications for both offensive and defensive strategies in modern warfare. For militaries deploying laser weapons, detailed knowledge of material degradation mechanisms enables the development of engagement protocols that maximize efficiency while minimizing collateral damage. This includes selecting optimal wavelengths, beam profiles, and dwell times tailored to the specific vulnerabilities of FR-4-based UAVs. For example, combining thermal and photochemical effects by employing multi-wavelength lasers could accelerate epoxy breakdown and shorten engagement times.

Conversely, UAV designers seeking to enhance survivability may explore countermeasures such as reflective coatings, sacrificial ablative layers, or alternative resin systems with higher thermal stability. However, such measures often increase cost and weight, undermining the economic advantages that make FR-4 attractive in the first place. In the context of asymmetric warfare, where mass production of inexpensive drones is a key strategy, the adoption of advanced protective materials is likely to remain limited. This dynamic suggests that laser weapons will retain their effectiveness against most FR-4-based UAVs for the foreseeable future.

Future research should focus on quantifying the thresholds for laser-induced failure in different UAV configurations. Laboratory experiments using controlled laser exposures can provide valuable data on heat transfer dynamics, delamination rates, and mechanical strength degradation. These findings can then be incorporated into computational models to predict battlefield performance under variable conditions. Such models would be invaluable for both weapon system developers and UAV manufacturers, enabling informed decisions about design trade-offs and countermeasure development.

4. Testing of the developed methodology

Experimental studies of the interaction of laser radiation with a sheet of FR-4 fiberglass composite with a thickness of 2 mm were carried out using a previously developed method [30]. Characteristics of laser radiation: laser power (P) is measured in W (1000…3000); deam diameter (D) is measured in mm (5.0…20.0); irradiation time (T) is measured in seconds (0.25…3.0); power density (Q) is the ratio of power to beam area, W/cm^2.

The following laser source were used fiber laser "MAX MFSC-6000M" with a power of up to 6.0 kW and a wavelength of radiation λ=1070 nm, manufactured by the company "Maxphotonics" (China). The parameters of the processing modes were changed discretely: laser radiation power 1.0 kW, 2.0 kW, 3.0 kW; laser beam incidence angles relative to the material surface 30º, 45º, 60º, 90º; laser radiation exposure time on the sample material 0.25 s, 0.5 s, 1.0 s, 2.0 s, 3.0 s; The diameter of the laser radiation spot on the surface of the carbon plate was 5.0 mm, 10.0 mm, 15.0 mm, 20.0 mm. Compressed air was supplied to the treatment zone to remove the destruction products.

Measurements of angles during the experiment are shown on Figure 1.

Radiant exposure (E) is the amount of energy per unit area, measured in J/cm^2 and calculated via this formula:

$$E= Q*T.$$

Figure 2 shows the change in radiant exposure values depending on the change in the time, when processing at an angle of 90°. (according to the scheme shown in Figure 1). In this graph, it can be noted that the “zone of uncertainty” in this case includes points of both complete penetration, partial penetration, and non-penetration. Despite this, the material is well amenable to laser processing regardless of the beam diameter – penetration cases occur at radiant exposure values of 250-300 J/cm^2.

Figure 3 shows the change in radiant exposure values depending on the change in the time, when processing at an angle of 30°C (according to the scheme shown in Figure 1). In this graph, it can be noted that for penetration

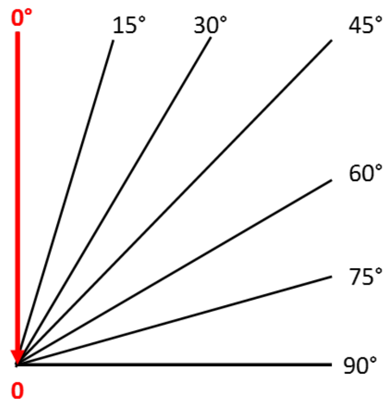

Figure 1. Measurement of angles from the laser beam to the sample

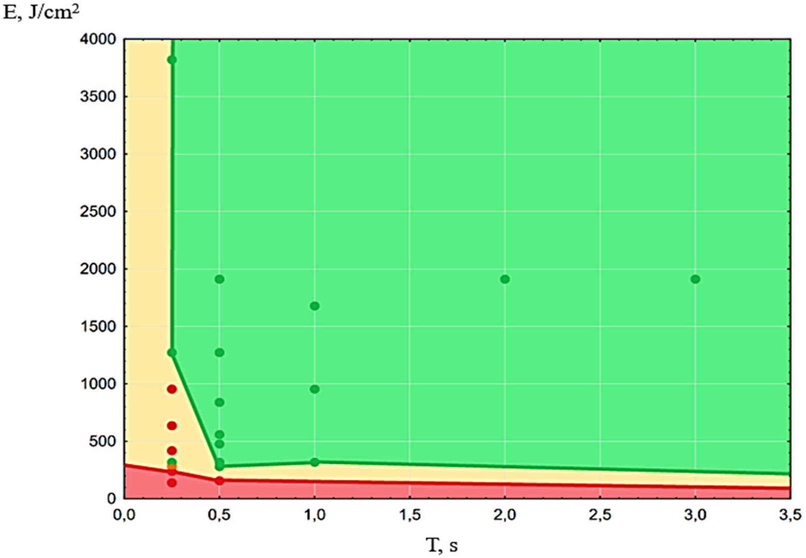

Figure 2. Graph of the dependence of the results of penetration on the value of radiant exposure and processing time, when processing at an angle of 90°C

of this material with a processing time of more than 0.5 s, it decreases to a level of 600-1000 W/cm^2. that the “zone of uncertainty” in this case includes points of both complete penetration and points of partial penetration, and points of non-penetration. At the same time, with increasing power, the required exposure value increases, which is associated with the need to hold a certain processing time.

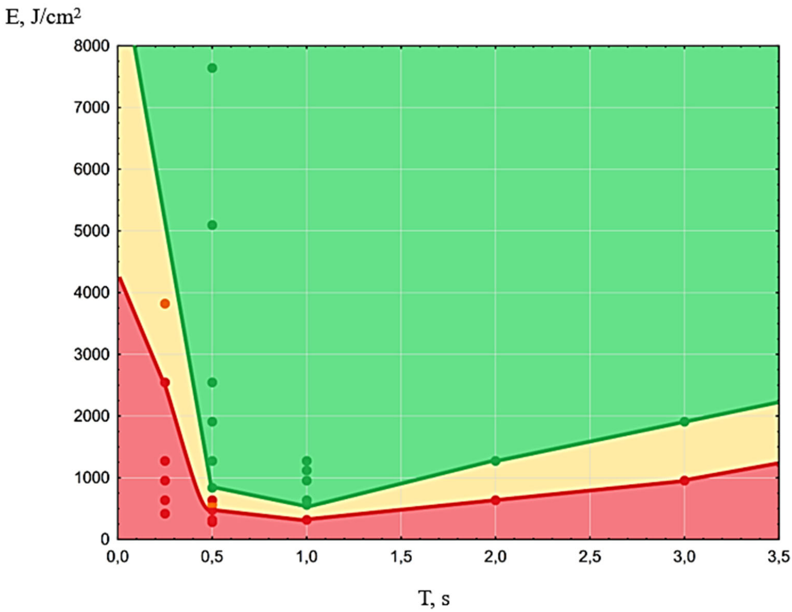

Figure 3. Graph of the dependence of the results of penetration on the value of radiant exposure and processing time, when processing at an angle of 30°C

Figure 4 shows the change in radiant exposure values depending on the change in the time, when processing at an angle of 45°C (according to the scheme shown in Figure 1). In this graph, it can be noted that the “zone of uncertainty” in this case tends to increase only due to the lack of data. Estimatedly, the critical reference line repeats the pattern observed at other angles – namely, with a processing time of more than 0.5 s, the level of the exposure value required for penetration becomes stable and practically evens out.

Figure 5 shows the change in radiant exposure values depending on the change in the time, when processing at an angle of 60°C (according to the scheme shown in Figure 1).

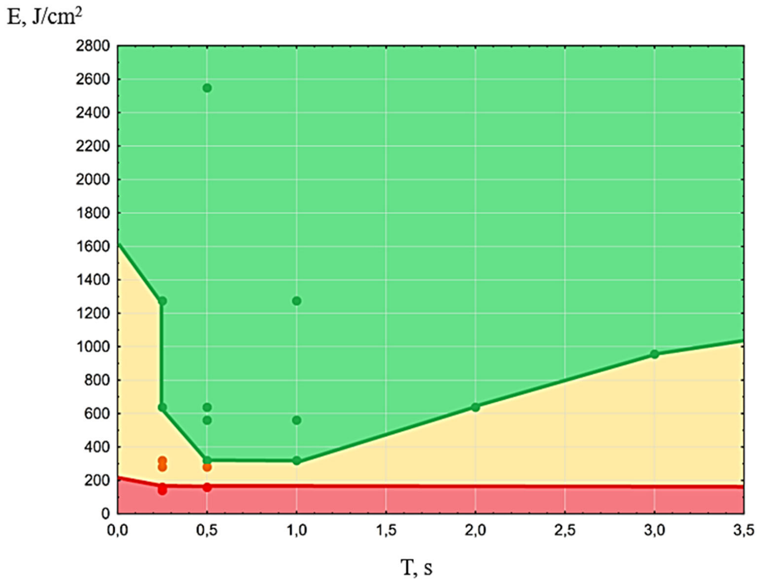

Figure 4. Graph of the dependence of the results of penetration on the value of radiant exposure and processing time, when processing at an angle of 45°C

The graph in Figure 5 shows that the material is well amenable to fiber laser processing, as the reference lines have a shape close to a straight line, regardless of the processing time. Breakthrough cases occur at energy exposure values from 320-500 J/cm^2.

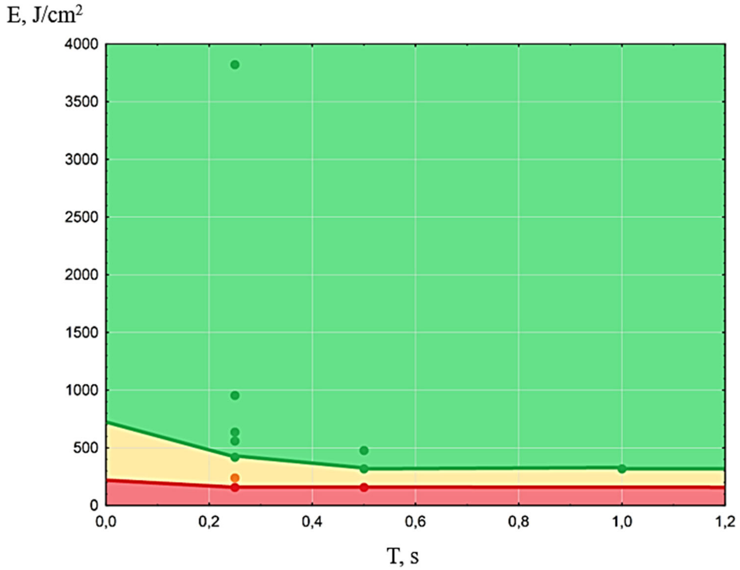

Figure 5. Graph of the dependence of the results of penetration on the value of radiant exposure and processing time, when processing at an angle of 60°C

5. Conclusions

FR-4 fiberglass composite has emerged as one of the most strategically significant materials in contemporary UAV design. Its unique combination of mechanical strength, thermal stability, electrical insulation, and affordability has made it a cornerstone of both military and civilian drone production. From improvised battlefield UAVs in Ukraine to industrially manufactured reconnaissance platforms, FR-4 fiberglass composite has demonstrated its versatility and reliability under a wide range of conditions.

The ongoing conflict in Eastern Europe has underscored the material's role in shaping the future of warfare. By enabling the rapid, decentralized production of low-cost drones, FR-4 fiberglass composite has contributed to a paradigm shift in military operations. This shift is not merely technological but also doctrinal, as armed forces worldwide adapt to the realities of mass UAV deployment and the new forms of threat and opportunity it creates.

While FR-4 fiberglass composite is unlikely to replace advanced aerospace composites in high-performance applications, its strategic importance lies in its accessibility and scalability. As research continues to refine its properties and expand its capabilities, FR-4 will remain a central player in the ongoing evolution of UAV design. Its story illustrates the profound impact that materials science can have on global security, economics, and the very nature of conflict in the 21st century.

The interaction of laser radiation with FR-4 fiberglass composite represents a complex interplay of thermal, photochemical, and mechanical processes. In the context of counter-UAV warfare, these interactions are of critical importance, as FR-4 serves as both a structural and electronic foundation for many modern drones. The degradation process begins with rapid heating and pyrolysis of the epoxy matrix, progresses through delamination and fiber exposure, and culminates in catastrophic structural failure. This multi-stage pathway makes FR-4 fiberglass composite highly vulnerable to even moderate levels of laser energy, particularly when combined with precise targeting and favorable atmospheric conditions.

The ongoing war in Ukraine has provided real-world validation of these principles, with laser weapons emerging as a promising tool for neutralizing the vast numbers of inexpensive UAVs deployed on the battlefield. As directed energy systems continue to mature, the study of FR-4 fiberglass composite degradation will play a central role in shaping future military tactics, UAV design philosophies, and international norms governing the use of laser technology in war. Ultimately, the struggle between UAV proliferation and counter-UAV innovation exemplifies the broader technological arms race of the 21st century, with materials science standing at the very heart of this evolving contest.

After analyzing the data obtained after conducting a series of experiments, it can be concluded that for piercing 2 mm thick FR-4 fiberglass composite using a fiber laser, the main characteristic of the processing mode is the processing time, which should exceed 0.5 s. Radiation during this time interval allows the material to pierce FR-4 fiberglass composite samples in the absolute majority of conditions presented in the experiment, even when using relatively low density values (about 1000 W/cm^2) and a large beam diameter (15-20 mm).

Funding.

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" (grant support No. 8/0166 dated March 03, 2025).

References:

1. Nefodova, L., Kushch, V., & Cherneha, T. (2024). Global arms market transformation and the rise of drone warfare: strategic lessons from Ukraine's experience. *Political Science and Security Studies Journal*, 5(3), 62-67. https://doi.org/10.33445/psssj.2024.5.3.6

2. Kunertova, D. (2023). Drones have boots: Learning from Russia's war in Ukraine. *Contemporary Security Policy, 44*(4), 576-591. https://doi.org/10.1080/13523260.2023.2262792

3. Hammes, T. X. (2024). I. The Promise of the Smart, Cheap and Many. *Whitehall Papers, 102*(1), 11-27. https://doi.org/10.1080/02681307.2024.2506245

4. Siora, O., Lukashenko, V., & Bernatskyi, A. (2025). An interdisciplinary study of the effect of laser radiation on carbon fiber-reinforced polymer, in the context of counteracting unmanned aerial vehicles. *History of Science and Technology, 15*(1), 195-215. https://doi.org/10.32703/2415-7422-2024-15-1-195-215

5. Wicaksono, D., & Setiawan, F. (2023). Penerapan metode manufaktur terbaru pada body drone UAV Skywalker. *Teknika STTKD: Jurnal Teknik, Elektronik, Engine, 9*(1), 201-208. https://doi.org/10.56521/teknika.v9i2.964

6. Rekatsinas, C. S., Dimitriou, D. K., & Chrysochoidis, N. A. (2024). A road map to the structural optimization of a Type-C composite UAV. *Aerospace*, 11(3), 211. https://doi.org/10.3390/aerospace11030211

7. Liao, K.-C., Liou, J.-L., Hidayat, M., Wen, H.-T., & Wu, H.-Y. (2024). Detection and analysis of aircraft composite material structures using UAV. *Inventions*, *9*(3), 47. https://doi.org/10.3390/inventions9030047

8. Stanislaus Arputharaj, B., Jayakumar, S. S., Solaiappan, S. K., Raja, V., Rajendran, P., Krishnamoorthy, M., ... & Ahmed, A. M. (2024). Comprehensive and validated computational investigations of structural integrity, aerodynamic behavior, and its turbulence characteristics on agricultural drone with and without payload devices. *Journal of Engineering, 2024*(1), 1386709. https://doi.org/10.1155/2024/1386709

9. Shcherbyna, O., Zadorozhnyi, O., & Stetsyshin, O. (2024). Passive antenna arrays in UAV communication systems. I*nternational Journal of Computer Network and Information Security (IJCNIS), 16*(4), 31-51. https://doi.org/10.5815/ijcnis.2024.04.03

10. Jha, S. K., Prakash, S., Rathore, R. S., Mahmud, M., Kaiwartya, O., & Lloret, J. (2022). Quality-of-service-centric design and analysis of unmanned aerial vehicles. *Sensors, 22*(15), 5477. https://doi.org/10.3390/s22155477

11. Vedrtnam, A., Negi, H., & Kalauni, K. (2025). Materials and energy-centric life cycle assessment for drones: A review. *Journal of Composites Science, 9*(4), 169. https://doi.org/10.3390/jcs9040169

12. Kumar, M., Yadav, V., Kwe, N. B., Savilov, S. V., & Singh, S. K. (2025). Investigation of flame-retarded epoxy resin fiberglass composite material-based coplanar waveguide patch antennas. *Macromolecular Symposia, 414*(1), 2400161 https://doi.org/10.1002/masy.202400161

13. Rudajevová, A., & Dušek, K. (2018). Influence of manufacturing mechanical and thermal histories on dimensional stabilities of FR4 laminate and FR4/Cu-plated holes. *Materials, 11*(11), 2114. https://doi.org/10.3390/ma11112114

14. Rodrigues, C. F., Blaga, L., & Klusemann, B. (2025). Thermal degradation and decomposition of FR4 laminate PCB substrates joined by Friction Riveting. *Applied Composite Materials,* 32(3), 879-893. https://doi.org/10.1007/s10443-025-10308-6

15. Ghewari, P., & Patil, V. (2025). Advancements in microstrip patch antenna design using nature-inspired metaheuristic optimization algorithms: A systematic review. *Archives of Computational Methods in Engineering, 32*, 3687–3732. https://doi.org/10.1007/s11831-025-10254-3

16. Ali, S. Z., Ahsan, K., ul Khairi, D., Alhalabi, W., & Anwar, M. S. (2024). Advancements in FR4 dielectric analysis: Free space approach and measurement validation. *PLoS One, 19*(9), e0305614. https://doi.org/10.1371/journal.pone.0305614

17. Veeraperumal Senthil Nathan, J. P., Navamani Chellapandian, M., Raja, V., Rajendran, P., Lee, I. E., Kulandaiyappan, N. K., ... & Varshney, D. (2025). Multi-Disciplinary investigations on the best flying wing configuration for Hybrid Unmanned Aerial Vehicles: A new approach to design. *Machines, 13*(7), 604. https://doi.org/10.3390/machines13070604

18. Ta, P. L., Tran, C. D., & Bach, G. D. (2022). Design and fabrication of an X-band low noise amplifier using FR-4 for military radar and ground station receiver applications. *VNU Journal of Science: Mathematics-Physics, 38*(2), 33-42. https://doi.org/10.25073/2588-1124/vnumap.4670

19. Kitazawa, T., Yamagiwa, T., Kitahara, R., Kim, Y., Chakarothai, J., Hayashi, Y., & Kasuga, T. (2022). A novel FDTD approach considering frequency dispersion of FR-4 substrates for signal transmission analyses at GHz band. *IEEE Transactions on Electromagnetic Compatibility*, 64(5), 1522-1532. https://doi.org/10.1109/TEMC.2022.3175376

20. Varma, D. K., & Ayyadurai, M. (2023, November). Design of square patch antenna for X band applications using RT-duroid substrate and comparing its gain performance with FR4 substrate. *AIP Conference Proceedings*, 2822(1), 020184. https://doi.org/10.1063/5.0172944

21. Bernatskyi, A., Lukashenko, V., Siora, O., & Sokolovskyi, M. (2024). Analysis of the application of lasers for counter-UAV purposes. *History of Science and Technology, 14*(2), 487-512. https://doi.org/10.32703/2415-7422-2024-14-2-487-512

22. Liu, W., Zhang, L., Wang, D., Meng, X., & Zhang, B. (2024). Application and key technologies of laser weapons in anti-UAV swarm operations. *Hangkong Xuebao/Acta Aeronautica et Astronautica Sinica, 45*(12), 329457. https://doi.org/10.7527/S1000-6893.2023.29457

23. Bernatskyi, A., & Sokolovskyi, M. (2022). History of military laser technology development in military applications. *History of Science and Technology, 12*(1), 88–113. https://doi.org/10.32703/2415-7422-2022-12-1-88-113

24. Huang, S., Fu, Z., Liu, C., & Li, J. (2023). Multi-objective optimization of fiber laser cutting quality characteristics of glass fiber reinforced plastic (GFRP) materials. *Optics & Laser Technology, 167*, 109720. https://doi.org/10.1016/j.optlastec.2023.109720

25. Sun, Y., Zheng, Z., Wang, Y., Yang, B., Wang, J., & Mu, W. (2022). PLA composites reinforced with rice residues or glass fiber – a review of mechanical properties, thermal properties, and biodegradation properties. *Journal of Polymer Research, 29*(10), 422. https://doi.org/10.1007/s10965-022-03274-1

26. Zhen, Y., Ma, Z., Gao, L., Wang, D., Wei, C., Lv, Y., ... & Jiang, M. (2023). Ablation behavior and microwave absorption performance of metamaterials irradiated by high-energy continuous-wave laser. *Materials & Design*, 225, 111502. https://doi.org/10.1016/j.matdes.2022.111502

27. Wu, J., Huang, S., Wang, X., Kou, Y., & Yang, W. (2024). Study on the performance of laser device for attacking miniature UAVs. *Optics, 5*(4), 378-391. https://doi.org/10.3390/opt5040028

28. Lyu, C., & Zhan, R. (2022). Global analysis of active defense technologies for unmanned aerial vehicle. *IEEE Aerospace and Electronic Systems Magazine, 37*(1), 6-31. https://doi.org/10.1109/MAES.2021.3115205

29. Liu, L., Xu, C., Zheng, C., Cai, S., Wang, C., & Guo, J. (2024). Vulnerability assessment of UAV engine to laser based on improved shotline method. *Defence Technology, 33*, 588-600. https://doi.org/10.1016/j.dt.2023.08.008

30. Bernatskyi, A., & Siora, O. (2024). Development and testing of a methodology for determining the effect of laser radiation parameters on the destruction of materials used to manufacture UAV. In: *Modern science: prospects, innovations and technologies : Scientific monograph,* (Part 1, pp. 1–30). Baltija Publishing, Riga, Latvia. https://doi.org/10.30525/978-9934-26-473-3-1