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ENERGETIC COMPOSITE MATERIALS FOR MICRO-INITIATION SYSTEMS: COMPOSITION-PERFORMANCE RELATIONSHIPS

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Abstract. *Introduction.* Micro-initiation systems are crucial for the advancement of smart combustible technologies, enabling highly localized and controlled initiation of energetic reactions at the microscale. These systems are essential in applications such as micro-chips, MEMS devices, and smart munitions, and they depend on energetic composite materials (ECMs) that effectively balance performance and safety. *Objective of the study.* This review examines the relationships between composition and performance in energetic materials (ECMs) used in micro-initiation systems. It focuses on the chemical, structural, and thermal characteristics that influence ignition sensitivity, energy release, and combustion behavior. Key materials—including copper(II) azide, HMX, RDX, CL-20, and TAGN—are evaluated alongside advanced carbon nanomaterials and nanocomposites that enhance safety and performance. Special attention is given to the role of graphene and conductive oxides in mitigating sensitivity, as well as the use of nano-engineered fuels to improve combustion efficiency. *Results and Discussion.* Emerging microfabrication and additive manufacturing techniques for producing miniaturized energetic architectures are also discussed. The integration of advanced materials chemistry with micro-engineering holds promises for the development of next-generation energetic systems. *Conclusions.* This review identifies challenges such as thermal stability, electrostatic safety, and predictive modeling, while highlighting future directions for designing safer, high-performance energetic materials.

Keywords: micro-initiation systems, energetic composite materials, copper azide, HMX, RDX, CL-20, TAGN, graphene, sensitivity mitigation, MEMS devices, energetic nanocomposites, nano-aluminum, combustion efficiency.

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1. Introduction

Micro-initiation systems represent a significant advancement in energetic technologies, facilitating the miniaturization and precise control of explosive and propellant systems. These systems are engineered to initiate energetic reactions on a microscale, leveraging primary explosives that deliver considerable energy within compact spatial limits [1]. Their increasing demand arises from their versatility across applications such as micro-energetic devices and smart munitions, where precision and operational effectiveness are critical. We view micro-initiation systems as essential enablers of advanced micro-energetic platforms, particularly in cutting-edge weaponry and aerospace innovations [2]. Serving as a key trigger in the energetic chain, they spark the detonation of secondary explosives or the combustion of propellants. Consequently, designing reliable and efficient micro-initiation systems is imperative to guarantee the performance and safety of these advanced devices.

As the demand for miniaturization escalates, there is an increasing requirement for advanced techniques to deposit and pattern energetic materials in micro-initiation systems. Traditional methods often fail to provide the precision and control necessary for microscale fabrication, underscoring the need for innovative approaches like micro-printing, electrodeposition, and self-assembly [3]. These modern strategies allow for the creation of complex energetic structures with tailored properties, thus facilitating the development of more effective and reliable micro-initiation systems.

Furthermore, the advancement of micro-initiation systems requires a comprehensive understanding of the fundamental mechanisms driving energetic initiation. This involves investigating key processes such as thermal energy transfer, chemical reaction dynamics, and shock wave propagation [4]. By deepening our knowledge of these phenomena, researchers and engineers can design more durable and efficient micro-initiation systems capable of fulfilling the stringent requirements of contemporary energetic applications.

Energetic Composite Materials (ECMs). Energetic composite materials (ECMs) represent sophisticated engineered systems that integrate energetic components, such as explosives or propellants, with non-energetic elements like binders, additives, or structural frameworks to achieve customized functional properties. This combination enables precise adjustment of critical performance factors, including energy release, sensitivity, mechanical strength, and thermal resilience, rendering ECMs highly versatile for a range of applications. Through alterations in the composition and structural arrangement of their constituents, ECMs provide adaptable design options, allowing for fine-tuned control over their behavior [5]. The significant thermodynamic capacity of ECMs stems from their energetic fractions, which release substantial energy upon activation, while non-energetic components enhance mechanical durability, improve processability, and reduce vulnerability to external influences.

Energetic composite materials (ECMs) are widely employed in polymer-bonded explosives and solid propellants, striking a balance between energy output and mechanical durability [6]. In polymer-bonded explosives, energetic crystals are embedded within a polymer matrix, which enhances structural integrity and minimizes sensitivity to impact and friction. For solid propellants, ECMs enable high energy density and controlled combustion rates, supporting efficient propulsion in rocket motors and various aerospace applications. Nano-sized energetic composite materials (nano-ECMs) represent a significant advancement in energetic material technology, expanding their applicability in explosives and propellants [7]. Composed of nanoscale energetic particles dispersed in a matrix, nano-ECMs demonstrate increased reactivity, improved combustion efficiency, and greater energy release. These unique properties make nano-ECMs particularly well-suited for advanced energetic systems like micro-initiators, where high performance and miniaturization are critical requirements.

Importance of Composition-Performance Relationships. Understanding the relationship between the composition of energetic materials and their performance characteristics is essential for predicting their effectiveness and safety. These relationships determine how materials respond to various stressors, including impact, friction, thermal exposure, and electrostatic discharge. By elucidating these interactions, researchers and engineers can create energetic materials tailored to meet specific application needs. The molecular structure of these materials plays a pivotal role in shaping their detonation performance and mechanical sensitivity [8]. The arrangement of atoms and the nature of chemical bonds within a molecule govern its stability, energy potential, and reactivity. For example, adding nitro groups (-NO_2) can boost a molecule's energy content, though this may also increase its vulnerability to impact and friction. Similarly, the crystalline arrangement of an energetic material affects its density, which in turn influences its detonation velocity and pressure.

The creation of novel energetic compounds hinges on a thorough understanding of the relationship between molecular structure and material properties. By carefully selecting and arranging atoms and functional groups, chemists can design innovative energetic materials with improved performance and enhanced safety profiles. This process often utilizes computational modeling and simulation tools to predict the properties of potential compounds before their experimental synthesis.

2. Key energetic materials used in micro-initiation systems

2.1. Primary explosives: copper(II) azide

Copper(II) azide (CA) stands out as an efficient primary explosive, attributed to its high energy density, which supports the effective initiation of secondary explosive reactions. However, its practical application is constrained by significant electrostatic sensitivity, presenting notable safety challenges during handling and integration into micro-initiation systems [10,11]. This heightened risk of unintended detonation from static charges highlights the necessity for stringent safety protocols to manage associated hazards.

One promising approach to mitigate the electrostatic sensitivity of copper azide involves crafting graphene-based composites [12]. Renowned for its exceptional electrical conductivity, graphene promotes the rapid dispersal of static charges, reducing the potential for accidental initiation. The incorporation of graphene into the copper azide matrix [13,14] yields a composite with reduced susceptibility to electrostatic discharge. The fabrication of these composites typically relies on methods such as freeze-drying and in-situ azidation, which enhance both the safety and performance profiles of CA composites [13, p., 15]. The freeze-drying technique involves quickly freezing a mixture of copper ions and graphene oxide, followed by sublimation of ice to create a porous structure [16]. Subsequently, in-situ azidation converts the copper ions into copper azide within the graphene framework.

The sensitivity of energetic materials to electric spark ignition plays a critical role in designing micro-initiation systems [17]. The energy threshold for spark-induced explosions must be carefully controlled to ensure both operational reliability and safety. As a result, modifying copper azide with graphene not only lowers its electrostatic sensitivity but also modifies its response to electric sparks, enhancing its suitability for micro-initiation applications.

2.2. Secondary explosives: HMX and RDX

High Melting Explosive (1,3,5,7-Tetranitro-1,3,5,7-tetrazocane, widely known as HMX or octogen) and Research Department eXplosive (1,3,5-Trinitro-1,3,5-triazinane, commonly referred to as RDX or cyclonite) are key secondary explosives in energetic composite materials, prized for their high energy content and moderate stability. These compounds are frequently combined with binders and other additives to produce customized composites for applications such as demolition charges and missile warheads [18-20].

Integrating HMX with glycidyl azide polymer (GAP) results in energetic composites that exhibit improved energy density and mechanical robustness, making them ideal for demanding solid propellant applications. GAP acts as both a binder and an energy enhancer, contributing to a composite with superior energy density and structural integrity, which is particularly beneficial for solid propellants requiring high energy release and durability [21-23]. We suggest that HMX-GAP composites may outperform RDX-based formulations in micro-initiation systems due to their enhanced mechanical properties, a potential area for further investigation.

RDX serves as a benchmark for evaluating the performance of new energetic materials, providing a reliable standard for comparing the attributes of emerging explosives [24-26]. Its well-established properties and extensive use across various applications make it an ideal reference for assessing the detonation velocity, pressure, and sensitivity of novel energetic compounds.

HMX-Al/MoO_3 composite explosives can be initiated with high precision using energetic semiconductor bridges (ESCBs), offering a controlled approach to triggering energetic reactions [27]. ESCBs utilize a small semiconductor bridge that produces heat upon electrical activation, effectively igniting the explosive material [28]. This method is particularly advantageous in micro-initiation systems, where accurate control and miniaturization are essential requirements. We propose that further optimization of ESCB design could enhance initiation efficiency in such systems, an area ripe for future research.

2.3. Other energetic materials

Hexanitrohexaazaisowurtzitane ($C_6H_6N_{12}O_{12}$, CL-20), a nitramine explosive with a distinctive cage-like structure, is distinguished for its exceptional detonation velocity, high density, and enhanced energy release, surpassing conventional explosives such as RDX and HMX. Recent advancements have seen CL-20 incorporated into 3D-printed energetic structures, demonstrating its adaptability to state-of-the-art additive manufacturing techniques for producing complex, miniaturized components in advanced weapon systems [29]. The material's high energy density and tunable detonation properties allow for precise control of energy release, which is crucial for applications requiring both explosive power and spatial accuracy [30]. Moreover, CL-20's compatibility with polymeric binders and modern fabrication methods paves the way for developing tailored energetic devices, positioning it as a leading candidate for next-generation military applications.

Triaminoguanidine nitrate ($CH_9N_7O_3$, TAGN), a nitrogen-rich compound, integrates effectively with glycidyl azide polymer (GAP) to form advanced energetic composites, offering a practical alternative to traditional HMX-based formulations [31]. Unlike typical high explosives, TAGN provides a favorable balance of energy output, thermal stability, and reduced sensitivity, making it an attractive option for next-generation propellants and explosive systems [32]. A key advantage of TAGN is its combustion profile, primarily producing hydrogen gas as a byproduct, which is particularly beneficial for specialized propellant applications like low-signature propulsion systems or insensitive munitions, where controlled energy release and thermal management are critical [33]. Furthermore, the synergy between TAGN and GAP allows for customizable mechanical and energetic properties [34], enhancing safety during handling and enabling flexible formulation approaches to meet diverse military and aerospace requirements. We suggest that exploring the scalability of TAGN-GAP composites could further broaden their practical implementation in such applications.

Silver azide (AgN_3) is recognized as an environmentally friendly primary explosive with excellent initiation properties, making it a fitting candidate for modern weapon systems that demand miniaturization [35]. Its lower toxicity compared to traditional lead-based explosives positions as an attractive alternative for applications where environmental sustainability is a priority.

The sensitivity of Al/ITO (aluminum/indium tin oxide) thermite to mechanical and electrical discharge stresses has been assessed, highlighting the potential of conductive oxides in energetic composites [36]. This study underscores the effectiveness of n-type semiconductors like ITO in mitigating electrostatic discharge sensitivity, thereby improving the safety of energetic materials during handling and transportation. We propose that further investigation into the scalability of ITO-based composites could enhance their practical application in micro-initiation systems.

3. Role of graphene and carbon-based materials

3.1. Graphene as a sensitivity mitigator

Graphene's superior electrical and thermal conductivity significantly enhances the safety of energetic composites by enabling the rapid dissipation of electrostatic charges [37]. Its ability to efficiently manage heat and electrical charges reduces the composite's susceptibility to external stimuli [38], making graphene a critical component for improving the safety and reliability of energetic formulations. Specifically, the incorporation of graphene can substantially lower the electrostatic sensitivity of primary explosives like copper azide, thereby enhancing their safety during handling and processing [39]. By providing a conductive pathway for static charge dispersal, graphene minimizes the risk of accidental initiation due to electrostatic discharge.

Graphene-based materials can be synthesized using diverse techniques, including hydrothermal self-assembly, which enables the production of composites with precisely tailored properties. This method involves subjecting graphene oxide dispersions to high-temperature and high-pressure conditions (typically 180–200 °C for 12–24 hours), allowing controlled nucleation and growth that shape the material's morphology and structure [40]. This versatility optimizes their performance in energetic composites by adjusting pore sizes (ranging from 2–50 nm) and layer alignment, enhancing mechanical strength and electrical conductivity (up to 10^6 S/m). For example, porous graphene frameworks, with specific surface areas exceeding 1,000 m^2/g, are employed to create copper azide ($Cu(N_3)_2$) composites, reducing sensitivity by 40% (from 0.1 mJ to 0.06 mJ electrostatic discharge threshold) while preserving energy density (~4 kJ/g) [41]. We propose exploring electrochemical deposition, which offers precise layer-by-layer control and scalability for industrial production, potentially increasing yield by 20–30 % and enhancing applicability in micro-initiation systems for MEMS and smart munitions, a promising direction.

3.2. Carbon nanomaterials for performance enhancement

The integration of diverse carbon nanostructures with distinct hybridization states—such as sp^2-hybridized graphene, sp^3-hybridized nanodiamonds, and sp-hybridized carbyne chains—significantly boosts the effectiveness of energetic materials by promoting synergistic physicochemical interactions [42–44]. This strategy capitalizes on the unique properties of various carbon allotropes, including their structural flexibility, electronic behavior, and thermal conductivity, to engineer energetic composites with improved reactivity and energy output.

Each carbon allotrope contributes specific advantages: graphene excels in electrical and thermal conductivity due to its delocalized π-electron system, while nanodiamonds provide enhanced thermal stability and opportunities for surface tailoring [45–47]. When combined, these materials form interconnected networks that optimize energy transfer and ensure uniform thermal decomposition of the energetic matrix.

At the nanoscale, these carbon nanostructures play a crucial role in modulating phonon–phonon interactions, redistributing vibrational energy, and enhancing interfacial energy transfer, directly influencing the reaction kinetics and thermodynamic pathways of energetic decomposition [48]. By carefully designing and spatially arranging these nanostructures, researchers can tailor energy release rates, ignition sensitivity, and combustion dynamics to suit specific needs, such as propellants, explosives, or pyrotechnics.

Additionally, carbon allotropes act as highly effective catalytic nano-additives. Their large specific surface areas, tunable surface properties, and unique quantum and electronic features enable them to accelerate the decomposition of energetic materials and support more complete combustion processes [49]. Notably, the surface chemistry of modified graphene or carbon nanotubes can lower activation energy barriers for redox reactions and promote hot spot formation, triggering rapid exothermic effects.

The inclusion of these nanostructures also greatly improves heat conduction within the composite, ensuring a consistent temperature profile across reaction zones. This enhanced thermal conductivity accelerates the reaction front's progression, resulting in faster, more controlled combustion and higher energy yields with improved performance metrics [50]. We propose that the targeted use of carbon nanostructures offers a viable route to developing next-generation energetic composites, enabling precise adjustments to their functional and energetic attributes. Further exploration into optimizing nanostructure ratios could unlock additional performance enhancements.

3.3. Applications of carbon materials

Carbon-based materials are extensively utilized across a broad range of energetic composites to boost their performance through enhanced electrical and thermal conductivity, improved chemical stability, and optimized energy release efficiency [51]. Their versatility stems from a variety of allotropic forms—such as graphene, carbon nanotubes (CNTs), fullerenes, nanodiamonds, and amorphous carbon—each contributing unique physicochemical properties that benefit energetic formulations.

The multifunctional nature of these carbon allotropes makes them highly compatible with both conventional and innovative energetic materials. For instance, conductive carbon nanostructures improve charge transfer processes, reduce sensitivity to electrostatic discharge, and promote uniform initiation of decomposition reactions [52]. Additionally, their inherent stability extends the composite's shelf life and thermal resistance, while their ability to enhance energy density and accelerate reaction rates supports more efficient energy release. When combined with energetic components—like nitramines (e.g., RDX or HMX), metallic fuels (e.g., aluminum nanoparticles), or oxidizers (e.g., ammonium perchlorate)—carbon materials often produce synergistic effects, improving combustion dynamics and overall energetic performance [53-55]. These enhancements arise from physical interactions, such as interfacial bonding and dispersion, as well as chemical interactions, including catalytic decomposition pathways, which can be refined through thoughtful material selection and formulation strategies.

The structural and surface properties of carbon nanomaterials can be finely adjusted to enhance their integration with energetic matrices. Modifications through oxidation, heteroatom doping (e.g., with nitrogen or boron), or the addition of specific functional groups can significantly influence dispersibility, compatibility, and catalytic activity. Moreover, manipulating porosity and specific surface area allows for precise control over adsorption behavior and thermal characteristics, enabling tailored regulation of ignition thresholds, combustion rates, and energy release profiles [56-58].

An emerging research area explores the controlled phase transformation of carbon nanostructures using external stimuli, such as combined electron and ion irradiation. This technique drives structural changes—such as converting amorphous carbon into graphitic regions or forming nanodiamond nuclei—profoundly impacting the material's electronic, mechanical, and catalytic properties [59]. These irradiation-induced alterations offer a powerful method for in-situ customization of nanocarbon behavior, supporting the development of advanced additives optimized for specific energetic applications. We propose that this approach could be extended to real-time tuning during composite fabrication, a direction worth exploring further.

In conclusion, the strategic integration and customization of carbon materials into energetic composites establishes a robust foundation for developing advanced, high-performance energetic systems. By exploiting the structural adaptability of carbon allotropes, such as graphene (sp^2) and nanodiamonds (sp^3), with high specific surface areas and their exceptional physicochemical properties—such as electrical conductivity and thermal stability — researchers can precisely regulate combustion dynamics, reduce sensitivity, and optimize energy release rates. This approach enables tailored energetic behavior for applications in propellants, explosives, and micro-initiation systems.

4. Applications for MEMS and micro-devices

4.1. Micro-initiators for smart munitions

Micro-scale initiators act as essential subsystems in smart munition technologies, serving as precise activation mechanisms for triggering warhead detonations and propellant ignition. These compact energetic units are engineered to provide rapid, reliable, and spatially confined energy release, ensuring consistent performance under varied operational conditions [60]. Given the stringent requirements of military use, micro-scale firing trains must exhibit exceptional reliability, thermal resistance, and mechanical strength to endure harsh environmental challenges such as shock, vibration, extreme temperatures, and prolonged storage.

Modern micro-initiator designs can be optimized for versatility, allowing seamless integration with both traditional high-performance energetics and emerging insensitive munition (IM)-compliant materials. This adaptability is a vital prerequisite for current and future defense systems, enabling safe deployment across platforms while meeting rigorous IM safety standards [61]. Incorporating flexible ignition profiles and modular energetic components into micro-firing trains allows these systems to cater to the specific activation demands of a wide array of materials, from conventional secondary explosives (e.g., RDX or HMX) to advanced IM-compatible formulations [62]. We propose that this multifunctionality could be further enhanced by developing standardized modular designs, a potential area for future exploration.

To promote wider adoption in the defense sector, there is a growing need for cost-effective, high-throughput microfabrication techniques. This includes advancing scalable approaches like microelectromechanical systems (MEMS)-based manufacturing, additive printing of energetic materials, and photolithography-compatible patterning of initiator elements [63]. The ability to produce reliable micro-initiators at reduced costs is key to transitioning from prototype development to operational smart munitions.

Micro-initiators form the fundamental energetic components of micro-energetic systems, facilitating the compact integration of ignition and detonation functions into efficient devices. Typically built from nanothermites, reactive multilayer foils, or MEMS-based energetic structures, these initiators offer highly localized and tunable energy release capabilities [64]. Their small size and responsiveness to electrical, optical, or thermal stimuli make them ideal for precise initiation in advanced weapon systems, autonomous guided munitions, and other micro-engineered platforms.

The continued evolution of micro-initiator technology is crucial for advancing intelligent, responsive energetic systems. By leveraging innovations in materials chemistry, micromachining, and formulation strategies, micro-firing trains are poised to deliver next-generation improvements in precision, safety, and effectiveness across diverse defense and aerospace applications.

4.2. Energetic materials in MEMS devices

The integration of energetic materials into micro-electro-mechanical systems (MEMS) represents a transformative step in designing compact, intelligent energetic devices. One standout material for this application is nanoporous energetic silicon, which combines the structural benefits of porous silicon with energetic functionalization. This material integrates seamlessly into standard microfabrication processes, ensuring compatibility with complementary metal–oxide–semiconductor (CMOS) electronics and other microelectronic platforms

[65]. The collaboration between energetic silicon and MEMS fabrication methods supports the development of monolithically integrated initiation systems, offering precise control over ignition timing, detonation spread, and localized energy release.

This approach is particularly well-suited for advancing next-generation MEMS-based Safing and Arming (S&A) mechanisms, which are vital for ensuring the safety, dependability, and controlled functionality of advanced energetic devices. MEMS S&A systems can combine mechanical interlocks, micro-actuators, and energetic micro-initiators into a single compact unit. Designed to respond to environmental cues or external commands, these systems can enable or disable initiation, keeping the device dormant until the precise moment of activation [66]. The application of energetic silicon in these systems enhances both passive and active safety features, bolstering resilience under challenging operational conditions. We suggest that further research into optimizing silicon porosity could refine these safety mechanisms.

Beyond silicon-based energetics, nanoscale silver azide (AgN_3) has gained prominence as an effective material for micro-initiator applications in MEMS technologies. With its fast detonation velocity, sensitivity to optical or thermal triggers, and adaptability to nanoscale fabrication, nano-AgN_3 serves as a key energetic compound in micro-scale firing trains [67]. Its nanoscale design improves initiation reliability and energy output control, making it highly suitable for integrated MEMS detonators and micro-pyrotechnic systems. The confined geometry of MEMS devices also helps manage the risks of sensitive energetics by restricting their use to specific reaction chambers and minimizing active material quantities.

Moreover, innovative additive manufacturing techniques, such as inkjet printing, have been successfully adapted to produce microscale energetic boosters, opening new avenues for high-resolution patterning and composite development. A significant example is the formulation and deposition of GAP/NC/DNTF (glycidyl azide polymer/nitrocellulose/dinitrofuranofuroxan) blends, which merge GAP's mechanical flexibility and binding capabilities with the rapid combustion and high energy density of NC and DNTF. Inkjet printing these blends allows precise placement of boosters within microreactors or PyroMEMS (pyrotechnic MEMS) systems [68]. This method provides exact control over layer thickness, compositional variations, and energetic loading, enabling the creation of complex energetic structures with reliable and adjustable performance. We propose that refining printing parameters could further enhance the precision and scalability of these boosters.

5. Challenges and opportunities

5.1. Overcoming sensitivity issues

Developing high-performance energetic materials often faces the critical challenge of balancing high energy release with acceptable safety levels. Potent compounds like RDX, HMX, and CL-20 exhibit heightened sensitivity to external stimuli such as friction, impact, electrostatic discharge, and temperature fluctuations, creating significant risks during handling, transport, and storage [69]. Therefore, reducing sensitivity while maintaining energetic effectiveness is a primary objective for advancing next-generation energetic formulations.

Various strategies have been explored to tackle this trade-off. One effective approach involves incorporating inert or semi-reactive additives that act as physical barriers or thermal buffers, dissipating localized energy and preventing hot spot formation. For example, polymer binders such as Viton or fluoropolymers can encapsulate sensitive particles, reducing mechanical sensitivity and enhancing matrix stability [70]. Additionally, molecular engineering techniques, such as incorporating electron-withdrawing groups or substituting heteroatoms, can improve the stability of high-energy molecules by decreasing electron density and strengthening lattice interactions within the crystal structure [71]. These design strategies not only increase thermal stability but also reduce shock sensitivity. However, we note that the use of polymer binders may slightly lower the overall energy density, a limitation that warrants further investigation for applications requiring maximum energy output.

The interplay between sensitivity and performance is governed by fundamental thermodynamic and kinetic principles. Increasing the enthalpy of formation typically enhances detonation velocity and pressure, but it often reduces activation energy barriers, inadvertently increasing sensitivity [72]. Thus, efforts to boost energy density must be accompanied by measures to mitigate the risk of accidental initiation.

A promising and innovative approach involves the use of conductive or semiconductive metal oxides, such as antimony trioxide (Sb_2O_3), zinc oxide (ZnO), or doped titanium dioxide (TiO_2), as additives in energetic composites [73]. These materials facilitate charge dissipation, minimize triboelectric buildup, and provide structural reinforcement, collectively reducing the likelihood of unintended ignition. Their electronic properties also help regulate heat transfer and energy localization, making them versatile additives that enhance both safety and combustion efficiency. We suggest that combining these metal oxides with graphene-based additives could offer a synergistic effect, further improving safety profiles, an area ripe for future research.

5.2 Enhancing energy release and combustion

Efficient combustion and rapid energy release are crucial for optimizing the performance of micro-initiation systems, where confined geometries and limited energy resources demand maximum output from minimal reactant volumes [74]. Precisely adjusting these factors is essential for creating reliable and scalable ignition systems for applications like micro-thrusters and micro-initiators.

Nano-aluminum (nAl) has emerged as a widely studied fuel due to its high oxidative enthalpy and advantageous reactivity properties. Its nanoscale size significantly increases the surface-area-to-volume ratio, speeding up combustion kinetics and reducing ignition delays. In microscale or volume-constrained systems, nAl-based formulations exhibit fast and complete combustion, substantially improving overall energy output and system responsiveness.

An alternative strategy to enhance combustion efficiency involves energetic composite structures with intimate mixed fuel and oxidizer components. By designing layered or core-shell architectures, researchers can control diffusion pathways, ignition thresholds, and reaction front progression. Incorporating combustion catalysts, such as transition metal oxides or carbon-based nanomaterials, further accelerates reaction rates and promotes more consistent and cleaner energy release. The deliberate pairing of fuel and oxidizer in nanoscale stoichiometric composites (e.g., Al/CuO, Al/Fe_2O_3, Al/I_2O_5) provides a flexible platform for customizing combustion characteristics. Fine-tuning variables like particle size, interfacial contact area, and mixing homogeneity allow precise control over burn rates, flame temperatures, and gas-phase product formation [75]. These tailored composites are particularly advantageous in microscale devices, where combustion efficiency directly impacts thrust performance and energy delivery. We propose that optimizing the stoichiometry of these composites could further enhance their performance in micro-thruster applications, a direction worth exploring. An overview of energetic materials is presented in Table 1.

Table 1 - Overview of energetic materials

Material	Chemical Formula	Crystal Density (g/cm³)	Detonation Velocity (m/s)	Sensitivity (Impact, friction)	Thermal Stability (°C)	Reference
Copper Azide	$Cu(N_3)_2$	3.25	~5,000	Extremely sensitive	~180	[76]
HMX	$C_4H_8N_8O_8$	1.91	~9,100	Moderate sensitivity	~280	[77]
RDX	$C_3H_6N_6O_6$	1.82	~8,750	Moderate	~210	[78]
CL-20	$C_6H_6N_{12}O_{12}$	2.04	~9,800	High sensitivity	~240	[79]
TAGN	$C_2H_4N_{10}$	1.72	~8,000	Sensitive	~220	[80]
Graphene (modifier)	C_{60}	~2.25	—	Inert	>3 000	[81]

In summary, Table 1 provides a comparative analysis of explosive strength (quantified by detonation velocity), stability, and sensitivity. Compounds like CL-20 exhibit high performance, albeit with elevated sensitivity. Conversely, additives such as graphene enhance safety and stability without contributing to the detonation process.

5.3 Future research directions

Despite notable advancements, the field of energetic materials continues to face significant challenges, particularly in developing formulations that combine enhanced safety, high energy density, and superior thermal resilience. Such innovative compounds are essential for progressing next-generation military platforms, aerospace propulsion systems, and civilian safety applications.

Energetic materials with exceptional thermal stability—capable of withstanding high temperatures without degradation or performance loss—are critical for extreme operational environments. Applications such as hypersonic propulsion, deep-space missions, and directed energy systems require materials with decomposition temperatures above 300 °C, low vapor pressure, and long-term storage durability. Research into nitrogen-rich heterocyclic compounds, metallized ionic liquids, and high-nitrogen polymers presents promising avenues for addressing these needs.

The persistent effort to develop thermally stable, high-energy, and low-sensitivity formulations drives innovation across materials chemistry, nanotechnology, and energetic system engineering. As interdisciplinary research progresses, we anticipate that the creation of safe, powerful, and versatile energetic materials will pave the way for transformative breakthroughs in both military and civilian technologies. Specifically, we propose that integrating machine learning models to predict thermal stability could accelerate the discovery of such materials, a direction ripe for exploration.

6. Conclusion

The evolution of micro-initiation systems represents a critical frontier in developing compact, precise, and high-performance energetic technologies. This review emphasizes the pivotal role of composition–performance relationships in designing energetic composite materials that achieve significant energy release while mitigating sensitivity and safety risks. Primary explosives such as copper(II) azide and silver azide exhibit outstanding initiation capabilities but require desensitization strategies, such as the integration of graphene, to ensure safe and reliable use in micro-scale devices. Conversely, secondary explosives such as HMX, RDX, and newer compounds like CL-20 and TAGN illustrate how strategic molecular design and binder selection can enhance energy output, mechanical strength, and thermal stability.

Advancements in carbon nanomaterials and conductive oxides have created new opportunities to improve the performance of electrochemical devices by optimizing thermal and charge management. These developments, alongside modern microfabrication techniques such as inkjet printing and MEMS-compatible structuring, facilitate unprecedented levels of miniaturization and integration.

Nevertheless, significant challenges persist. Balancing energy density with safety, achieving consistent three-dimensional moldability of energetic nanocomposites, and developing predictive models for performance under varied conditions remain key areas for ongoing research. We propose that future advancements could benefit from hybrid materials combining the high energy density of CL-20 with safety enhancements from graphene and conductive oxides, potentially revolutionizing smart munition applications.

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МИКРО-ИНИЦИАЦИЯЛЫҚ ЖҮЙЕЛЕРГЕ АРНАЛҒАН ЭНЕРГЕТИКАЛЫҚ КОМПОЗИЦИЯЛЫҚ МАТЕРИАЛДАР: КОМПОЗИЦИЯ МЕН ӨНІМДІЛІК ҚАТЫНАСТАРЫ

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Түйіндеме. *Кіріспе.* Микро-инициация жүйелері энергетикалық смарт технологияларды дамыту үшін маңызды болып табылады, бұл микро масштабтағы энергетикалық реакцияларды оқшаулауға және бақылауға мүмкіндік береді. Бұл жүйелер тиімді өнімділік пен қауіпсіздікті біріктіретін энергетикалық композиттік материалдарды (ECMS) пайдалануға негізделген чиптер, MEMS құрылғылары, смарт оқ-дәрілер және т.б. сияқты қолданбаларда қажет. *Зерттеудің мақсаты.* Бұл шолу мақаласы микро-инициация жүйелерінде қолданылатын энергетикалық материалдардың (ECMS) құрамы мен пайдалану сипаттамалары арасындағы байланысты қарастырады. Композицияның тұтануға сезімталдығына, энергияның бөлінуіне және жану сипаттамаларына әсер ететін химиялық, құрылымдық және жылу сипаттамаларына назар аударылады. Мыс (II) азид, октоген, гексоген, CL-20 және TAGN сияқты негізгі материалдар қауіпсіздік пен өнімділікті арттыратын озық көміртекті наноматериалдар мен нанокомпозиттермен бірге бағаланады. Сезімталдықты төмендетудегі графен мен өткізгіш оксидтердің рөліне, сондай-ақ жану тиімділігін арттыру үшін нанотехнологиялық отындарды пайдалануға ерекше назар аударылады. *Нәтижелер және талқылау.* Миниатюралық энергетикалық архитектураларды құру үшін микроөңдеу мен қосымша өндірістің жаңа технологиялары талқылануда. Материалдардың озық химиясын микроинженериямен біріктіру келесі ұрпақтың энергетикалық жүйелерін дамыту перспективаларын ашатыны атап өтілді. *Қорытындылар.* Бұл шолу мақаласында термостабильділік, электростатикалық қауіпсіздік және композициялық композицияларды болжамды модельдеу сияқты проблемалар анықталған, сонымен қатар қауіпсіз және тиімділігі жоғары энергетикалық материалдарды әзірлеудің болашақ бағыттары көрсетілген.

Түйінді сөздер: микро-инициациялық жүйелер, энергетикалық композиттік материалдар, мыс азиді, HMX, RDX, CL-20, TAGN, графен, сезімталдықты азайту, MEMS құрылғылары, энергетикалық нанокомпозиттер, нано-алюминий, жану тиімділігі.

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ЭНЕРГЕТИЧЕСКИЕ КОМПОЗИЦИОННЫЕ МАТЕРИАЛЫ ДЛЯ СИСТЕМ МИКРОИНИЦИИРОВАНИЯ: ВЗАИМОСВЯЗЬ СОСТАВА И ХАРАКТЕРИСТИК

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Резюме. *Введение.* Системы микро-инициирования приобретают важное значение для развития энергетических смарт технологий, позволяя локализовать и контролировать энергетические реакции в микромасштабе. Данные системы необходимы в таких областях применения, как микросхемы, MEMS-устройства, интеллектуальные боеприпасы и др., основанных на использовании энергетических композитных материалов (ECMS), сочетающих эффективно производительность и безопасность. *Цель исследования.* Данная обзорная статья рассматривает взаимосвязь между составом и эксплуатационными характеристиками энергетических материалов (ECMS), используемых в системах микро-инициирования. Основное внимание уделяется химическим, структурным и тепловым характеристикам, которые влияют на чувствительность состава к воспламенению, выделение энергии и характеристики горения. Такие ключевые материалы как азид меди (II), октоген, гексоген, CL-20 и TAGN, оцениваются наряду с передовыми углеродными наноматериалами и нанокомпозитами, которые повышают безопасность и производительность. Особое внимание уделяется роли графена и проводящих оксидов в снижении чувствительности, а также использованию нанотехнологичных топлив для повышения эффективности сгорания. *Результаты и обсуждение.* Обсуждаются новые технологии микрообработки и аддитивного производства для создания миниатюрных энергетических архитектур. Отмечается, что интеграция передовой химии материалов с микроинженерией открывает перспективы для разработки энергетических систем следующего поколения. *Выводы.* В данной обзорной статье определены такие проблемы, как термостабильность, электростатическая безопасность и прогнозное моделирование композитных составов, а также намечены будущие направления для разработок более безопасных и высокоэффективных энергетических материалов.

Ключевые слова: системы микроинициирования, энергетические композиционные материалы, азид меди, октоген, гексоген, CL-20, TAGN, графен, снижение чувствительности, MEMS-устройства, энергетические нанокомпозиты, наноалюминий, эффективность сгорания.

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