

# Nanothermites: Applications, Limitations, Safety Considerations, and Future Prospects

Anamika<sup>1</sup>, Sonia Chalia<sup>2</sup>, Manish Naagar<sup>3</sup>

<sup>1</sup> Department of Aerospace Engineering, Amity University Haryana

<sup>2</sup> Nanotechnology Wing, Innovative Science Research Society, Shimla, Himachal Pradesh, India

<sup>3</sup> Department of Aerospace Engineering, School of Engineering & Computing, Dev Bhoomi Uttarakhand University, Dehradun, Uttarakhand, India

**Abstract-** The continuous advancement of energetic materials is critical for modern defence, aerospace propulsion, space exploration, and high-performance pyrotechnic applications. Among these, nanothermites—thermite compositions containing at least one nanoscale component—exhibit superior energy density, rapid reaction kinetics, and high combustion temperatures, making them highly attractive for next-generation energetic systems. Their unique properties, including high linear burning rates, tunable reaction heats, and the ability to form hybrid energetic compositions, enable their use in diverse applications such as propellant formulations, micro-thrusters, and reactive materials. However, their widespread adoption faces several challenges. Issues such as the formation of condensed combustion products, which contribute to two-phase flow losses in propulsion systems, and their heightened sensitivity to electrostatic discharge (ESD) pose significant safety risks. Additionally, storage stability and scalability remain major concerns. This study explores the opportunities presented by nanothermites, critically examines their limitations, and discusses key safety considerations. Finally, future research directions are outlined to address existing challenges and enhance the applicability of nanothermites in both civilian and military domains.

**Keywords-** Nanothermites, Energetic Materials, Nanoenergetics, Metastable Intermolecular Composites (MIC), Metal Oxide Nanoparticles, Propellants.

## I. INTRODUCTION

Energetic materials (EMs) are substances that store chemical energy and can liberate this chemical energy to perform various effects, such as detonation, deflagration, and burning, accompanied with both heat (thermal) and pressure effects. EMs can be classified into various categories, i.e., explosives, propellants, and pyrotechnics [1]. One of the groups of pyrotechnic compositions is thermite compositions, so-called thermites [2]. Thermite reaction is an exothermic redox reaction consisting of metal fuel and metallic oxide. They have been used for combustion synthesis of materials as well as other metallurgical or pyrotechnic applications such as welding or as incendiaries. Various fuels are used

like aluminium, magnesium and titanium and metal oxidizers like CuO, MnO<sub>2</sub> and Fe<sub>2</sub>O<sub>3</sub> etc [3]. In a stoichiometric mixture, all of the oxygen required to oxidize the fuel can be obtained from the metal oxide so that, in theory, thermites do not require any ambient oxygen to react [4]. The prototypical thermite reaction is shown in the equation below:



Here, A is a metal fuel and BxOy is a metal oxide.

Thermite formulations are often compared based on "reactivity." Historically, the reaction "propagation rate" has been one of the most common ways to evaluate thermite reactivity. Propagation rates are influenced by both chemical reaction kinetics and thermal transport kinetics. As such, they show the

expected trends with parameters affecting the intrinsic reactivity of a formulation like chemistry and particle size but are also configuration-dependent [4]. Since nanothermites are mixtures rather than single compounds, the mass-transport efficiency between the reactants dominates their reaction kinetics, thus many efforts have been made to increase the number of contact sites between fuels and oxidizers [5]. The reduction in thermite fuel and oxidizer particle sizes, ranging from micrometre to nanometre scale dimensions, considerably increases the surface area to volume ratio, allowing more fuel to be in direct contact with its oxidizer. Nanoscale particles permit greater intermixing and reduce the diffusion distance between fuel and oxidizer particles. As a result, the reaction progresses with a maximum rate and offers high energy release rates and high pressures. These thermites composed of nano-sized materials exhibit higher combustion characteristics when compared to their micron-sized relatives [1].

## II. NANO-THERMITES

Nanothermites or metastable intermolecular composites (MIC), made up of metal and metal-oxide nanoparticles as fuel and oxygen donor, respectively, have been of great interest due to their greater energy density and higher reactivity than micromolecular energetics [6]. Nanothermites were considered to be a modification of classical thermite formulations, in which the dimensions of phases formed by the components of the formulations were on the order of nanometres [2]. Thus, Nano-thermite contain particle of metal fuel and metallic oxide

in nano-size. The fuel and oxidizer are mixed in a specific ratio and then heated, causing them to react and form a highly energetic compound [7]. The electronegativity of metals used as fuels is a crucial factor when designing nanothermites. Metals with electronegativity values between 1.5 and 2.5 on the Pauling scale are usually preferred. This is because a good fuel for nanothermites should have strong reducing ability, high energy output, and good density. It should also produce some gases during reaction, have a low melting point, be stable, safe to handle, and work well with other materials in the

mixture [8]. Aluminium (Al), boron (B), silicon (Si), magnesium (Mg) and titanium (Ti) are the most commonly used fuels in nanothermite compositions.

In turn, copper(II) oxide (CuO), iron(III) oxide (Fe<sub>2</sub>O<sub>3</sub>), molybdenum(IV) oxide (MoO<sub>2</sub>), bismuth(III) oxide (Bi<sub>2</sub>O<sub>3</sub>) and tungsten oxide(VI) (WO<sub>3</sub>) are the most common examples of oxidising agents. Aluminium nanoparticles are widely utilized as fuel in nanothermites due to their low cost, easy availability, high energy density, and significant heat of combustion. Among the various nanothermite formulations, the Al/CuO system is the most extensively researched and is frequently regarded as a model system. However, its ignition and combustion processes are limited by a native alumina (Al<sub>2</sub>O<sub>3</sub>) layer that naturally forms on the surface of aluminium particles. As a result, ongoing research is focused on improving the flammability of aluminium and lowering its ignition temperature .

## III. IMPACT ON NANO-SIZED PARTICLES IN THERMITE COMPOSITION

### Greater Surface Area

Nanothermite is different from traditional thermite in that the particles used in nanothermite are extremely small, typically less than 100 nanometres in size [7]. A decrease in the particle size increases the available surface of the particles and the rate of energy release. The fundamental process influencing the combustion efficiency and energy release in nanothermites is interfacial diffusion, which determines heat and mass transfer. As the area of contact between nanoscale particles is higher than conventional thermites, this larger area of contact affects combustion velocity and efficiency during energy release in nanothermites [9]. Nanosizing of the ingredients of propellants leads to an increase in burn rate and in performance [10]. Thus, metastable intermolecular composite (MIC) takes advantage of the unique properties of nano-scale particles, which in general offer the large specific area and lower melting temperature. Since the larger specific area facilitates the faster reaction rate and the depressed melting point, resulting in a lower ignition temperature, the MIC has been of great interest in

the micro-energetic field where the amount of the reactants is restricted [11].

**Homogeneity**

In comparison with thermite compositions, whose components are micrometric in size, nanothermites are typically more homogeneous, exhibiting lower combustion induction times, high reaction heats and higher combustion velocities, typically up to 1000 m/s. Better contact between the fuel and the oxidising agent also results in extremely high reactivity, resulting in high sensitivity to initiating stimuli [12].

**Reduced Diffusion Distance and Ignition Time**

A decrease in the activation energy leads to an increase in the reactivity of nano-Al powder because these particles react extremely fast. The ignition time is the time taken by the hot gas to come in contact with the propellant and cause the emission of light. It is reported that the reduction in the fuel and oxidizer particles size reduces the diffusion distance between them thus increasing their intermixing and reaction rates and leading to less ignition times [13]. Fig 1 illustrates this effect, showing that nano-Al composites ignite 99.8% faster than micrometre Al composites, with ignition time dropping from 6 seconds to 12 milliseconds. This drastic reduction is attributed to the nanoscale properties of Al, particularly its size-dependent melting temperature [14]. Therefore, the ignition and combustion time for nano-sized Al are reduced as compared to micron-sized Al powder.

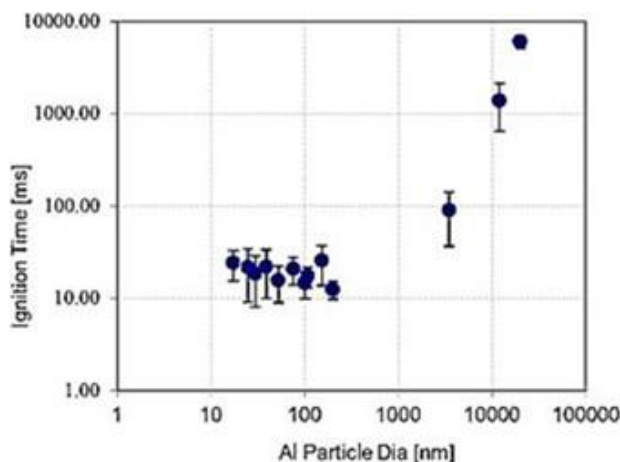


Figure 1: Ignition Time (ms) v/s Al Particle Dia (nm) Graph [14]

NanoAl particles release their equivalent heat in a shorter time than micron-sized Al, and if oxidation of Al particles occurs near the surface of the propellant, the heat flow released reflects very rapidly towards the surface of the propellants, which can thus increase the burn rate [10].

**Increased Sensitivity**

Nanoscale thermites can be sensitive to both shock and impact or one of the two based on the metal oxide as compared to the thermites on micron-scale that are typically rather insensitive to shock and impact [13]. Research has demonstrated that incorporating additives can effectively reduce the mechanical sensitivity of nanothermites. A study has demonstrated that an efficient friction desensitization of an Al/WO<sub>3</sub> nanothermite can be achieved using carbon as a desensitizing agent while still maintaining acceptable reactive properties [15].

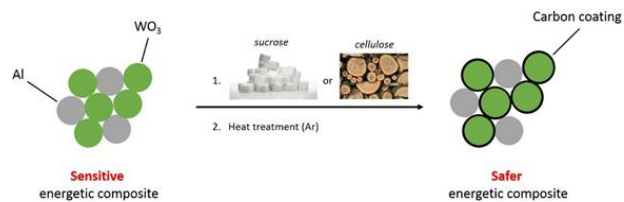


Figure 2: Carbon Coating of Energetic Composite for Reducing their Sensitivity [15]

Furthermore, Nanothermites are highly sensitive to electrostatic discharge (ESD), meaning even a small static spark can ignite them. Studies have shown that some nanothermites can be triggered by as little as 0.125 microjoules of static energy—an amount that can easily build up on a person. This makes them dangerous to handle without proper precautions [16].

### Comparison between Nano-Sized and Micro-Sized Thermites

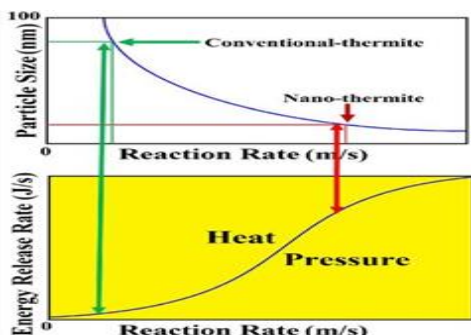


Fig 3: Comparison between reaction rate and Energy release rate of Conventional thermite and Nano-thermite [17]

Thus, Nano-sized particles (nm) and micron-sized particles ( $\mu\text{m}$ ) have distinct characteristics, each with their own advantages and disadvantages. Micron-sized particles are characterized by low cost and ease of production. They exhibit slow reaction speeds, high ignition temperatures, comparatively lower power density, and reduced sensitivity to ignition by impact, friction, heat, and ESD. Additionally, micron-sized particles have a lower energy release rate compared to nano-sized particles. On the other hand, Nano-sized particles offer reduced ignition and combustion time, high reaction rate, increased burning rate, enhanced mass transport, lower activation energy, and a high specific surface area. However, they come with challenges such as handling and storage dangers, high sensitivity to electrostatic discharge (ESD), particle agglomeration, and reduced energy density [13].

## IV. SYNTHESIS METHODS OF NANO-THERMITES

There are Various ways to synthesize Nano-thermites which include physical mixing, sol gel process, Vapour Deposition, Arrested reactive milling (ARM), etc described as follows:

### Physical Mixing of Nano-Powders

It is the Mechanical mixing of fuel (nano-Al) and oxidizer in a liquid (e.g., acetone, hexane) using

ultrasonic waves or powerful mixers, followed by evaporation and fine mesh sieving to prevent agglomeration. This method is Simple and widely used, and burning rate goes up to one thousand times that of macroscale thermite [1]. The method does not need large-scale instruments, is simple to operate, and has a wide application range.

For example, Al/CuO tEMs are conveniently prepared by the ultrasonic mixing method. Studies have shown that the maximum pressurization rate occurs in Al-rich thermite composites, which provides valuable references for designing other tEMs with better exothermic performance. However, while this method is simple and effective for screening valuable thermite energetic materials, it does not offer advantages in film-forming or combined applications with different devices [18]. The primary limitation of physical mixing is that it requires the use of nanoscale particles, which may not always be readily available commercially [19]. Also, there is potential for agglomeration and less uniform mixing is observed compared to advanced methods [1].

### Sol-Gel Process

In the Sol-Gel process, aluminum nanoparticles are incorporated into an oxidizer matrix as the system transitions from a colloidal solution ("sol") to a gel. The removal of the solvent, leading to the formation of a xerogel or aerogel, helps to prevent collapse, resulting in a structure with high porosity [1]. The Sol-Gel process involves three main steps: hydrolysis, condensation, and drying.

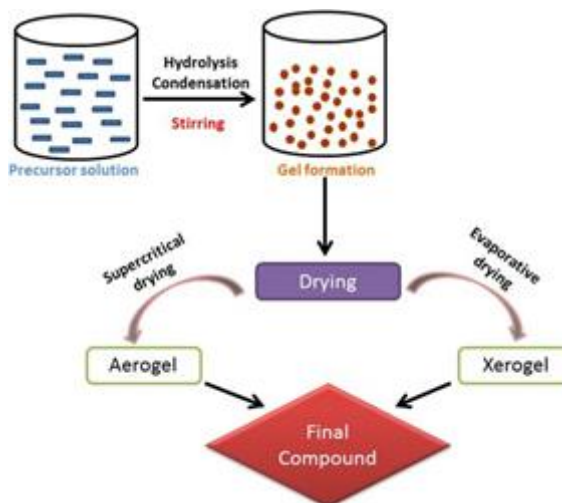


Figure 4: Sol-Gel process [13]

It is considered an economical and low-temperature process, which enables the production of novel energetic materials with desired properties. Studies have shown that sol-gel composites, such as Ta/WO<sub>3</sub> nanocomposites, exhibit improved heat release (30-35% greater than powder mixtures) due to the presence of carbon derived from organic precursors or solvent residues. These nanocomposites also demonstrate better resistance to ignition by spark, friction, and impact, highlighting the potential benefits of sol-gel in producing safer and more efficient energetic materials [13]. This method ensures highly intimate mixing of fuel and oxidizer; uniform nano-scale particles and pores. Despite its advantages, limitations include High porosity, challenges in scalability, and maintaining control over particle size and morphology remain [1].

### Vapor Deposition (VD)

In Vapor Deposition, thin films of nano-thermite materials (e.g., Ti/Al, Ti/C, Al/CuO) are created by exposing a substrate to volatile precursors, which are gaseous or evaporated compounds that decompose, react, or condense onto the surface, forming uniform nanoscale layers with precise control over thickness and composition. This method reduces diffusion distances between fuel and oxidizer (10–1000 times compared to physical mixing), enhancing reactivity and minimizing impurities [1]. Layered vapor deposition offers fine control over layer thickness, and nearly all commonly used metalloids, metal oxides, and metals can be deposited by adjusting the deposition parameters [13]. However, it requires specialized equipment and is limited to thin-film applications [1]. While this approach simplifies theoretical modelling due to the dense and distinct reactive multilayer nano foil (RMF) geometry, it remains expensive, difficult to scale, and faces challenges with premixing and maintaining minimal bilayer spacing. Additionally, factors such as interfacial free energies and chemical/elastic strain can disrupt the integrity of the layers [13].

### Arrested Reactive Milling (ARM)

ARM combines reactive milling and nanotechnology to create nanothermites with controlled reactivity by precisely managing parameters like time, temperature, and environment to prevent unwanted reactions [20]. It is a high-energy ball milling process that mechanically mixes metal with metal oxide under controlled conditions, initiating exothermic reactions. It is an effective method for producing energetic nanocomposites [1]. For example, as illustrated by fig 5, the process begins with adding raw materials, including aluminium (Al), iron oxide (Fe<sub>2</sub>O<sub>3</sub>), glass beads, and ethanol, into a milling container. The ball milling step ensures thorough mixing and refinement of particle sizes, improving contact between reactants and enhancing reaction kinetics. Ethanol serves as a dispersing agent, preventing particle agglomeration and oxidation during milling. Finally, the mixture undergoes baking at 50°C for 1 hour, which aids in solvent evaporation and results in a dry, well-mixed thermite composite [21].

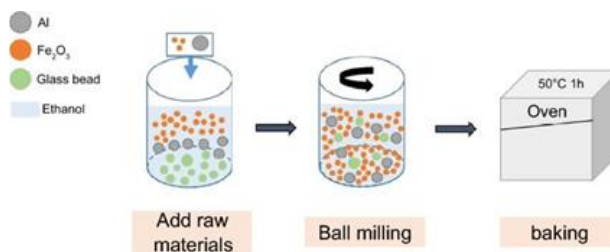


Figure 5 : Arrested Reactive Milling (ARM) [21]

This method has been used to fabricate various NEMs (e.g., Al/MoO<sub>3</sub>, Al/Fe<sub>2</sub>O<sub>3</sub>, Al/CuO) and is valued for its scalability, low cost, and ability to blend materials that other methods struggle with. Recent advancements include a secondary milling process with softer conditions for better particle distribution and flowability without reducing reactivity. Research also shows that using acetonitrile as a milling agent in Al/CuO nanocomposites results in a low-temperature exothermic peak around 600 K, improving ignition and propagation velocity. ARM has further been applied to complex compositions, such as Al/CuO combined with Cu(NH<sub>3</sub>)<sub>4</sub>(NO<sub>3</sub>)<sub>2</sub> for enhanced gas generation, and ternary NEMs like MgAl/CuO/nitrocellulose, which exhibit lower activation energy and improved energetic

performance [20]. Risk of mechanical ignition and safety concerns during preparation are associated with this method [1].

### **Additional Methods**

In addition to commonly used methods such as mechanical mixing, sol-gel processes, vapor deposition, and arrested reactive milling, several other techniques are employed to synthesize nanothermites. The vapor phase condensation method creates aluminium nanoparticles by cooling gaseous metal with an inert gas. The electrical explosion of wires (EEW) method generates ultra-fine metal powders using high-voltage pulses supplied to metal wires, these metal wire vaporizes and turn to plasma (~10,000 K). As the plasma rapidly expands and cools down, tiny nanoparticles of metal condense out of it. The hydrothermal synthesis method has been applied to produce oxidizer nanoparticles like CuO, Fe<sub>2</sub>O<sub>3</sub>, and Bi<sub>2</sub>O<sub>3</sub>, which are integral to energetic systems. Hydrothermal synthesis involves dissolving metal precursors in water, then heating the solution in a sealed, high-pressure vessel to promote controlled nanoparticle formation. The resulting oxidizer nanoparticles (e.g., CuO, Fe<sub>2</sub>O<sub>3</sub>) precipitate out and are collected for use in nanothermites. Furthermore, techniques such as polymer matrix encapsulation and surfactant self-assembly, which create structured nanothermites by coating nanoparticles with polymers or arranging them using surfactants, have been used to fabricate Fe<sub>2</sub>O<sub>3</sub> nanoparticles and Fe<sub>2</sub>O<sub>3</sub> nanotubes–Al nanoparticle superthermites, offering improved combustion characteristics and energy release. These advanced methods contribute to a better understanding and control of nanothermite properties for various applications [13].

## **V. APPLICATIONS OF NANO-THERMITES**

Nanoenergetic composites exhibit a wide range of properties that can be significantly adjusted by modifying various parameters, making them suitable for numerous applications. Since nanoenergetic composites are relatively new in the field of energetic materials, many potential applications have been proposed by researchers, though testing for these applications has yet to be conducted [22].

The potential applications of nanothermite span various fields, including the following:

### **Industrial and Metallurgy Applications**

Nanothermite has a wide range of applications across various fields due to its high energy release and precise controllability. It is employed in cutting and welding for industrial precision, utilizing its intense heat [23]. Thermite reaction is widely utilized in welding processes. Since welding with thermite formulations fills the internal contact surfaces with metal, the produced welds are highly durable, corrosion-resistant and conduct electricity well. The Goldschmidt (aluminothermic) reaction and other reactions jointly labelled as “thermite processes” have also found application in metallurgy, as means for extracting pure metals from their ores without the use of carbon-bearing additives [2].

### **Energetics, Defence and Aerospace Technologies**

In controlled demolitions, it can be used for safely bringing down buildings with minimal collateral damage. In pyrotechnics, nanothermite contributes to fireworks by generating intense heat and vibrant colours. In military applications, nanothermite is being researched as a potent, controlled explosive for munitions. Researchers are also exploring its integration with materials like aerogels or carbon nanotubes to create nanothermite composites with enhanced properties for aerospace and defence [24]. Nanothermite has been studied for its potential use in the aerospace industry, as it could be used as a highly efficient propellant or in the manufacture of advanced materials, such as high-temperature-resistant coatings and composites [25].

### **Microdevices and Ignition Systems**

Nanothermite has also been explored for specialized applications such as nanoenergetic gas generators (NGG), microthrusters, and micropropulsion systems, where its high detonation velocity and pressure impulse enhance performance. It is also being investigated for microelectromechanical systems (MEMS) and microactuators, enabling precision-controlled energetic reactions on a small scale. Nanothermites also hold promise in gun primers, where their tunable sensitivity to thermal stimuli enables them to replace harmful lead-based

compounds [13]. Another notable application is in electric igniters, widely used across industries such as propellants, pyrotechnics, and explosives. Known as electric matches, these igniters facilitate spark ignition in applications ranging from fireworks displays to rocket propulsion. They feature a resistive bridge wire with a flammable head that ignites when current passes through the wire. A key limitation of traditional igniters is the use of toxic lead compounds, which pose environmental risks. By replacing these with non-toxic nanothermites, a significant environmental benefit can be achieved [26].

### **Biological and Medical Prospects**

Another emerging area is its use as a biocidal agent, with certain nanothermite formulations generating biocidal gases that effectively destroy harmful microorganisms, making them suitable for defence against biological threats. Furthermore, nanothermites are being researched for molecular delivery applications, where their controlled energy release can be harnessed for pressure-pulse-based microoperation of bacterial cells and other soft materials [13].

## **VI. LIMITATIONS OF NANO-SIZED PARTICLE IN THERMITE COMPOSITION**

While the introduction of nanosized fuel and oxidizer particles into energetic materials has provided significant benefits in increasing burning rates and reducing ignition time, there are some major constraints that have limited further investigation, characterization, and implementation of these nanomaterials. Their nanometre scale dimensions, and the inherently high surface areas reduce their usability, e.g., similar solids loading cannot be achieved. This is because nanoparticles, due to their extremely small size and high surface area, tend to agglomerate and require larger amounts of dispersing media to remain stable.

As a result, achieving the same concentration of solids as with larger particles becomes difficult, leading to lower effective solids loading and ultimately affecting the material's mechanical strength, stability, and overall performance [22].

Nanothermites can be used in many applications, but their performance is limited because they mainly react in solid or liquid phases, making heat and mass transfer less efficient. To solve this problem, scientists have developed nanothermites mixed with gas-producing energetic materials to improve their reaction [12]. Nanothermites, though producing high energy density when burned, have a slow rate of energy release and low gas generation, limiting their use as propellants alone [12,27].

Additionally, nanosized aluminium particles in thermite reactions present further challenges that impact their performance. One major limitation is the complexity of the aluminothermite reaction, which is influenced by size-dependent surface interactions, varying mixing mechanisms, and uncertain bulk properties. Moreover, aluminium nanoparticles (Al NPs) are highly reactive in air, leading to the rapid formation of a thin aluminium oxide passivation layer. This oxide shell, typically a few nanometres thick, significantly reduces the amount of pure aluminium available for the reaction. For instance, in a 25 nm Al nanoparticle with a 3 nm oxide shell, over 60% of its volume consists of aluminium oxide rather than reactive aluminium. Furthermore, this oxide layer acts as an encapsulation, creating compressive pressure on the aluminium core and hindering its reactivity. These factors negatively impact the efficiency of nanothermite reactions, making it essential to develop strategies to mitigate

these limitations [11]. Reducing the particle size of high explosives, while increasing their sensitivity to external stimuli, can result in a reduced shelf life. This introduces a trade-off: although nanosizing explosives can increase sensitivity to external stimuli, it often comes at the cost of diminished thermal stability. This diminished stability means that thermites made from nanosized particles could have a reduced shelf life and increased handling hazards. Therefore, when deciding whether to replace micrometre-sized energetic materials with nanosized ones, the potential conflict between increased sensitivity and reduced thermal stability must be carefully considered, as it could affect both safety and performance [10].

## VII. CHALLENGES AND SAFETY CONCERNS

Safety is a critical concern when working with nanothermite due to its high reactivity and energy release, making mishandling or accidental ignition potentially dangerous. Strict safety protocols must be followed during its synthesis, storage, and use to prevent accidents. Additionally, concerns about its potential misuse in destructive activities highlight the need for strict regulations and controlled access to ensure responsible use and prevent it from falling into the wrong hands. Concerns over its military use and potential for terrorism have led to increased scrutiny. As research on nanothermite continues, strict oversight remains essential to ensure its safe and responsible application [28]. Key challenges in nanothermite research include high sensitivity, aging resistance, and the need for phlegmatizers to control combustion and enhance safety. Scaling up production remains difficult due to excessive costs and complexity, while minor variations in particle size significantly impact performance. Additionally, limited knowledge of toxicity poses concerns, especially given global efforts to reduce harmful compounds in explosives [2]. One of the important questions confronted by the scientific community is the combustion performance of nanothermites as a function of storage time. Limited studies exist on their long-term stability under varying environmental conditions, requiring further investigation [22].

## VIII. ADVANCEMENTS AND FUTURE SCOPE

The study of nanoenergetics has revitalized the interest in metal combustion, for example, for energy production and propulsion and opened new fields of study, such as micropyrotechnics, which includes studies on nanothermites and nanointermetallics and the integration of energetics on electronic chips [22]. Nanothermites were initially developed as a safer alternative to toxic lead-based energetic materials in percussion primers, an effort that remains ongoing due to environmental concerns.

Their ability to generate a rapidly propagating combustion and shock front makes them strong candidates for replacing lead-based primary explosives. While their primary application is in lead-free initiation systems, recent research has expanded their potential uses to areas such as gas generation, micropropulsion, and molecular delivery [2].

Among the several nanothermite-based EMs, graphene-based energetic materials show enormous promise to be a suitable candidate for various applications. Quantification of functional groups in FGS (functionalized graphene sheets) and correlation with synthesis methods is necessary to produce these NEMs with reproducible and reliable combustion characteristics. Furthermore, quantitative correlation of the ignition parameters such as ignition energy, ignition delay, and the method of ignition to the sensitivity parameters is essential. Since graphene-based NEMs are showing excellent potential with enhanced and tunable combustion performance, especially at reduced sensitivity to ESD (electrostatic discharge), it is pertinent to study the aging behaviour of these energetic formulations under harsh conditions .

## IX. SUMMARY

Nanothermites have emerged as a groundbreaking advancement in energetic materials, combining the unique properties of nanotechnology with the high energy density of thermite reactions. Their ability to generate intense heat, rapid combustion, and controlled energy release makes them highly desirable in various applications, including military, aerospace, industrial, and scientific fields. The fine-tuning of their reactivity and ignition properties allows for greater efficiency and precision in uses such as propulsion systems, welding, and microscale energetic devices.

However, while nanothermites offer numerous advantages over conventional thermites, their increased sensitivity and potential safety risks pose significant challenges. Handling and storage require stringent safety measures, and efforts to improve their stability remain a key area of research. Additionally, the scalability of production and cost-

effectiveness of large-scale implementation are ongoing concerns that must be addressed before nanothermites can see widespread adoption.

Despite these challenges, continuous advancements in nanomaterials and synthesis techniques are paving the way for safer, more efficient, and more versatile nanothermite formulations. With ongoing research and development, these materials hold the potential to revolutionize high-energy applications, offering innovative solutions to industries that require controlled yet powerful energy release. As scientists and engineers refine their understanding of nanothermites, they may unlock new possibilities that push the boundaries of energetic material technology, leading to safer and more effective applications in the future.

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