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Applications of boron and derivatives in defense industry: Mini review

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Abstract

Boron is the 51st most common element in the earth's crust and is usually found in nature not in pure form but in the form of borate compounds (e.g. borax, boric acid, and boric acid salts) in combination with oxygen. This semi-metal element in group 13 of the periodic table has historically been used in glass, ceramics, and antiseptic products, but today it has become a strategic material in many fields from energy technologies to nanotechnology. Boron, which plays a critical role, especially in renewable energy systems and battery technologies, increases the efficiency of photovoltaic cells in solar panels and increases the energy density and lifetime of lithium-ion batteries. While boron hydrides gain importance in the storage and release of hydrogen, boron carbide increases safety by providing neutron control in nuclear reactors. In the defence and aerospace industry, boron carbide and boron nitride, which are used in the production of light and durable materials, are preferred for their high strength and chemical stability. In the field of nanotechnology, boron nanotubes and boron-based nanomaterials enable groundbreaking applications in energy storage, industrial catalysts, and sensor technologies. In addition, boron compounds attract attention in the biomedical field with their anti-cancer properties and wound healing-promoting effects. In the agricultural sector, boron contributes to sustainable agricultural practices as a key component of fertilizers that support plant growth and increase productivity. Boron also plays a role in various physiological functions as an essential trace element for humans and plants. Although excessive intake can lead to toxic effects, the positive effects of boron on nutrition and health show that it is not a poison, but rather an essential nutrient for life. Thanks to these versatile uses, boron stands out as an indispensable element in the energy, materials, and biotechnology fields of the future.

Keywords: *Boron, Defence Technology, Boron Carbide, Nanotechnology.*

1. Introduction

Boron is a semi-metal (metalloid) element in group 13 of the periodic table, which is highly unique in its chemical nature [1]. Although it is abundant in the earth's crust, it is usually found in nature not in pure form, but as compounds such as borates and boric acid salts [2]. Boron, which is the fifth in the periodic table, is the only nonmetal in Group IIIA. Its electron configuration is $1s^2\ 2s^2\ 2p^1$ in the ground state, and it has a total of five electrons. However, despite this electron structure, boron always behaves trivalently in its chemical compounds, and it is not common for it to lose electrons by simply forming a cation. The atomic radius of boron is quite small, and the first ionization energy is high (800.5 kJ/mol); the second and third ionization energies are much higher (2426.5 and 3658.7 kJ/mol). Therefore, the boron atom forms a sp^2 hybridized valence structure by exciting a 2s electron and mixing the remaining 2s electron with the 2px and 2py orbitals. The resulting three sp^2 hybrid orbitals allow boron to form three B–X σ bonds. These bonds are covalent because the atomic properties of boron are not suitable for ionic bonding. For this reason, BX_3 type compounds mostly have a planar and triangular geometric structure [3]. In geological environments, the boron element is not found free and mostly forms compounds only with oxygen. With rare exceptions, boron is not observed to form direct bonds with other elements in fluorinated compounds such as $NaBF_4$ and avogadrite ($(K, Cs)BF_4$). In biological systems, boron is mainly found in the form of organic compounds and these compounds are generally defined as structures containing boron-oxygen (B–O) bonds. This group includes orthoborates ($B(OR)_3$, $(RO)B(OR')_2$ and (RO)B(OR')(OR")) and borates of polyhydroxyl alcohols. In addition, compounds containing boron–nitrogen (B–N) are also valuable in this context; because these bonds are structurally similar to carbon–carbon (C–C) bonds and have isoelectronic properties [3]–[5].

Boron has been used mostly in traditional fields such as glass, ceramics, and detergent industries for many years, today, with the developing technology and scientific research, it stands out as a strategic element in various fields such as energy, defense, electronics, medicine, agriculture and nanotechnology [6]. Boron plays a key role in the transition to sustainable energy by increasing the efficiency of photovoltaic cells in solar energy systems, increasing energy density in lithium-ion batteries, and providing effective solutions with boron hydride derivatives in hydrogen storage systems [7]. At the same time, research on the applications of boron and its derivatives in fuel cells has begun to be encountered quite frequently [8]. Boron minerals, usually in the form of borates, are formed by precipitation from volcanic gases or hot springs. Borax and sassolite are prime examples of such deposits, and the formation of these minerals occurs when shallow saline and alkaline tertiary lakes dry up [9]. Such lakes are called "playas". Prominent boron minerals include compounds such as borax ($Na_2O.2B_2O_3.10H_2O$), kernite (rasorite), colemanite ($Ca_2B_6O_{11}.5H_2O$), ulexite, and sodium calcium borate ($NaCaB_5O_9.8H_2O$) [10]. Worldwide reserves of boron minerals are about 380 million tons [11], with a significant portion of these reserves located in Türkiye, which holds about 72% of the world's boron reserves. Türkiye holds a large portion of the world's boron reserves. The reserve amount of known boron deposits in Türkiye is approximately 3.2 billion tons, which accounts for approximately 72% of the world's boron reserves. Türkiye's boron deposits are concentrated in the provinces of Eskişehir and Kütahya, and stand out as one of the leading countries in the world's boron production [12]. Türkiye's boron deposits make it one of the largest suppliers of boron and boron components worldwide, and the main sectors where these minerals are used include agriculture, ceramics, glass, nuclear energy and advanced technologies [13]. Other major boron producing countries include Chile, China, Peru, Russia and the United States [4].

Boron can be used in many areas as mentioned. However, its use as a neutron absorber has been seen as quite valuable. Boron naturally has two main isotopes, ^{10}B and ^{11}B. The neutron absorption efficiency of boron is based on the high absorption cross-section of the ^{10}B isotope in particular [14]. The neutron absorption reaction of boron is defined as the "(n, α)" reaction and this feature allows boron to effectively absorb neutrons in thermal reactors. Natural boron contains 19.8% of the ^{10}B isotope, while the rest consists of the ^{11}B isotope [15]. Neutron absorption in the low energy range is quite high for natural boron, making it ideal for use in thermal reactors. As with other elements, the absorption cross-section decreases greatly as the neutron energy increases, while the cross-section of the ^{10}B isotope remains more constant from low to high energies [16]. This feature makes boron an effective neutron absorber material in fast neutron reactors. Boron is also widely used in commercial fast neutron reactors in the form of boron carbide (B4C) enriched to the $^{10}B/^{11}B$ isotope ratio. An advantage of boron, compared to other neutron-absorbing materials, is that the reaction products (helium and lithium) are formed as stable and non-radioactive isotopes. In addition, refractory and rare earth metal borides have superior thermophysical properties for high-temperature applications and have the potential to be used as control/shutdown rods in Generation IV nuclear reactors [17].

Boron has another advantage compared to other neutron-absorbing materials: The reaction products, helium, and lithium, are stable and non-radioactive isotopes. Therefore, the use of boron control rods minimizes radiation emission and heating problems during the shutdown of nuclear reactors [18]. However, the fact that boron produces helium during the (n, α) reaction can create some difficulties in the design of control rods. In addition, secondary reactions with high-energy neutrons can be important in terms of reactor waste because they are the main source of tritium production. The advantages of boron carbide and refractory metal borides include low density, high melting point and hardness, chemical inactivity, and excellent thermal and electrical properties [19]. Therefore, boron and its components are highly potential materials for advanced technology applications.

The effectiveness of boron as a neutron absorber is particularly associated with the high absorption cross-section of the ^{10}B isotope. With a ^{10}B content of about 20%, natural boron has a very high neutron absorption in the low-energy neutron range, making it an excellent candidate for use in thermal reactors [20]. These properties make boron effective in the medium and fast neutron energy ranges. Another important use of boron is in neutron capture therapy (NCT), a form of radio-chemotherapy used to treat cancer and some forms of arthritis [21]. In 1932, just four years after the discovery of neutrons, biophysicist G.L. Locher of the Franklin Institute introduced the concept of NCT [22]. The boron NCT technique is advantageous because it is non-radioactive, readily available, and easily integrated into tumor cells [23].

Another study of boron, refractory and rare earth metal borides are suitable for space applications due to their attractive properties such as high melting points (>3000 °C), thermal conductivity, low coefficient of thermal expansion, maintenance of strength at high temperatures, good thermal shock resistance, oxidation resistance, and erosion resistance [24]. Zirconium diboride (ZrB_2) and hafnium diboride (HfB_2) are the leading candidates for such borides because of their oxidation resistance, high melting points (>2700 °C), and low vapor pressures. Oxides such as zirconium dioxide (ZrO_2) and hafnium(IV) oxide (HfO_2) are formed during the oxidation of these borides and remain stable even at high temperatures. Boron oxides, on the other hand, have a low melting point and high vapor pressure and evaporate away from the system. For this reason, ZrB_2 and HfB_2 are considered superior to other metal borides for ultrahigh-temperature applications. Rare earth metal borides similarly have potential for such applications [25].

In addition, boron carbide, which increases safety by providing neutron absorption in nuclear power plants, is also widely used in the production of high-strength, lightweight, and durable composite materials in the defense and aerospace industry [26]. While boron nitride is preferred in nanotechnology and electronics applications thanks to its graphene-like structure and high-temperature resistance, boron nanotubes and other boron-based nanomaterials enable groundbreaking developments in energy storage, catalyst systems, and sensor technologies [27]. The role of boron in biological systems is also attracting increasing attention. Boron, which is understood to be essential for various physiological functions in human and plant metabolism, shows positive effects on health when taken in appropriate amounts; it stands out with its bone health, immune system support, and wound healing accelerator properties. In the agricultural sector, boron is an important micronutrient element that supports plant growth and is widely used in the content of fertilizers that increase productivity [28]. Boron and its derivatives have also been used in hydrogen production. In practice, sodium borohydride or dimethyl aminoboron derivatives have been preferred in hydrogen production. However, there are still shortcomings that need to be investigated [29], [30].

However, the actual applications of these materials are limited due to production and consolidation difficulties. High melting points, low self-diffusion coefficients, and contamination with oxide layers on the surface make these compounds difficult to densify [31]. These problems have stimulated research to improve the sintering and densification processes. To improve the sinterability of carbide and boride materials, the sintering temperatures can be lowered by adding a suitable sinter additive [32]. Such additives can also provide additional benefits such as oxidation resistance and fracture toughness. Preparation of refractory/metallic borides has been reported using many methods such as direct reactions of the elements, carbo/boro/metallothermic reductions, and chemical vapor deposition. Consolidation of these materials is done using advanced sintering processes such as conventional pressureless sintering, hot pressing, hot isostatic pressing, spark plasma sintering, microwave sintering, rapid sintering, and chemical vapor infiltration [33].

Considering all these uses, boron is not only an ancient industrial material but also an energy-efficient, environmentally friendly, and technology-development strategic material. In this review, the physical and chemical characteristics of boron and its ancient and modern uses will be described in detail, and its functions and potential in key areas such as energy, nanotechnology, biomedicine, and agriculture will be evaluated [34]. The aim is both to compile existing knowledge and to provide perspectives that will guide future research and technological applications.

2. The Role of Boron Derivatives Applications and Importance for the Defense Industry

Boron draws attention as an important material in industrial applications thanks to its physical and chemical properties [35]. The use of boron and borate derivatives in the field of metal coating is of great importance, especially in critical sectors such as the defense industry. Such coatings increase the durability of metal surfaces and provide resistance to harsh conditions such as abrasion, corrosion, high-temperature effects, and friction. In the defense industry, metal surfaces must be equipped with superior properties for strategic equipment such as military vehicles, ammunition, rockets, and aircraft to operate efficiently for a long time. Borate coatings play a very critical role in this field in terms of material engineering and applied technology [36].

2.1. Effect of Boron and Borate Coatings on Metal Surfaces

When applied to metal surfaces, borate compounds form a strong protective layer that increases the resistance of these surfaces against corrosion. Boron has a feature that prevents corrosion reactions that occur especially as a result of oxidation and contact with acidic environments [37]. Borate coatings eliminate problems such as rust and oxidation that occur on metal surfaces, especially as a result of contact with oxygen, and contribute to the longevity of the surface [38]. This property is of utmost importance, especially in defense industry vehicles such as submarines, land vehicles, and aircraft. Vehicles in the military-defense industry are constantly exposed to harsh environmental elements, seawater, humidity, chemical agents, and high temperatures [39]. Under such conditions, metals upon which borate coatings are applied provide long life in service by surviving such extreme conditions. Boron also strengthens the mechanical characteristics of the metal by forming a covering layer within the microstructure of the metal [40].

The corrosion resistance-increasing effect of boron derivatives is also extremely important for defense equipment operating in environments with high salinity rates such as submarines [41]. These coatings also protect metal surfaces from the negative effects of seawater, deter rusting, and thereby lower maintenance requirements. In addition, the water-repellent properties of borate coatings protect engine systems used in military vehicles from externalities. For the military industry, these properties increase the durability of the vehicle and its ability to maintain function [42].

2.2. Effect of Borate Coatings on High Thermal Conditions

Another significant feature provided by borate derivatives in metal coatings is heat resistance. Borate coatings prevent expansion at the surface of the material due to hot temperature effects and reduce metal deformation[43]. This attribute is of high importance in defense applications, mainly for rocket and aircraft engines as well as other high-temperature system parts. Borate coatings protect the integrity of the metal from tiny fractures that are fabricated on metal surfaces under high temperatures [44].

Under high temperatures, expansion of metal surfaces can cause deformation in metals, which leads to deterioration of mechanical properties [45]. Boron minimizes such adverse effects and protects the structural hardness and integrity of the metal even at high temperatures. Defense applications, especially engines and ammunition systems, are exposed to extreme temperatures. Under these conditions, borate coatings limit thermal expansion and secure materials to perform effectively [46]. The use of borate coatings on aircraft and jet engines is a very significant factor in enabling engines to operate effectively and safely at even top speeds. Temperature resistance offered by borate derivatives is also an enormous advantage, especially for missile and rocket technology [47]. When rocket engines operate under high temperatures, these coats protect engine components from temperature stress, thus maintaining the performance as well as ensuring the safety of the rocket. Also, borate coatings help sustain the long-running life of fast-moving engines to reduce maintenance hours and increase operating hours [48].

2.3. Improvement of Friction Resistance and Mechanical Properties

Borate coatings enhance the performance of metal surfaces through the reduction of friction resistance. Borate coatings greatly lower the wear rate due to friction by introducing hardness into metal surfaces. Borate coatings find application in high-performance applications, particularly automobile engines, aircraft engines, and other precision machinery. In military applications, high-performance coatings make military equipment and systems more durable and reduce the need for maintenance [49]. This provides a significant benefit, especially to army aircraft and vehicles traveling at high speeds. Friction is one of the significant causes of wear in moving parts, and borate coatings eliminate such negative impacts and extend the life of the parts. Second, borate coatings harden metal surfaces, thus improving mechanical strength and fewer deformation and wear [50]. It can be understood that borate coatings play a pivotal role in precision instruments such as aircraft engines and also provide an important advantage in defense vehicles. Borate coatings ensure engine components wear out less and function efficiently for a longer period [51]. This is an extremely important factor in terms of the continuity of military operations.

Also, Boron carbide, which is one of the derivatives of borates, is a wear-resistant coating material with extremely high hardness. Boron carbide coatings are used especially on cutting tools, molds, and parts requiring high heat resistance [52]. These coatings protect metal surfaces from external factors, especially corrosive conditions, and extend the life of these parts. In the defense industry, boron carbide coatings provide high performance for rocket engines, armor, and other military equipment. Boron carbide resists wear on surfaces, allowing machines to operate more efficiently and for longer periods. In armor production, boron carbide is used together with ceramic armor and composite materials to increase ballistic resistance. Such coatings make armor more resistant to external factors and increase the safety of military vehicles and personnel [53]. In addition, boron carbide coatings are used in military machines operating under high temperatures and pressures, especially in rocket engines and aircraft engines operating at high temperatures, and extend the life of these parts [54].

2.4. Potential of Boron and Boron Derivatives for Ceramic Armor Applications

The development of armor materials in the defense industry has gained great importance over time to provide more effective protection. In this context, advanced ceramics are at the center of modern armor systems thanks to their high ballistic performance and low weight [55]. Ceramic armor materials have been an important part of armored vehicles and personal protection equipment since World War I, and during the Vietnam War, lightweight armor applications were developed using materials such as boron carbide [56]. Today, boron and boron derivatives attract attention with the superior mechanical properties and low densities they offer in ceramic armor applications. Ceramic materials are preferred in the defense industry especially due to their high ballistic performance. Among the main advantages of these materials is their ability to effectively disperse and break this energy in cases where bullets and other projects hit at high speeds [57]. Materials such as alumina (Al_2O_3), silicon carbide (SiC), and titanium diboride (TiB_2) stand out among traditional ceramic materials. However, these materials also have some disadvantages; For example, alumina has a higher density than others, while silicon carbide and titanium diboride are more expensive [58]. Boron derivatives have significant potential for ceramic armor materials. Boron carbide (B_4C), as a low-density material, significantly reduces the weight of armor systems while also offering high hardness and wear resistance [59]. These properties qualify boron carbide to be a suitable material for light armor. Boron carbide is especially highly preferred in transportable armor systems (e.g. light armored vehicles and body armor). Additionally, boron derivatives are utilized in ceramic composites to provide enhanced ballistic effectiveness in armor systems [60]. The superior properties of boron in this area increase the durability of armor materials and significantly improve the effectiveness of armor systems [58]–[60]. Boron and boron derivatives have been used as the second phase in ceramic composites in the past few years, improving the mechanical behavior of the materials. For example, the addition of boron carbide to the alumina matrix reduces the density of the material but increases its hardness and strength. These ceramic composites offer tremendous advantages where traditional ceramic armor materials are not sufficient. Alumina-boron carbide composites provide greater protection, especially against high-velocity ballistic projectiles [61]. Additionally, these composites can typically be obtained by lower-cost manufacturing techniques so that they are available in large quantities for the defense industry. The ceramic composites can be reinforced with boron derivatives and also with other high-strength materials. For example, combinations with materials such as silicon carbide or titanium diboride increase the mechanical robustness of the armor as well as reduce the overall weight of the armor [62], [63]. Such composites enable the development of lighter and more effective armor systems. Boron carbide provides particularly high durability, erosion resistance, and wear properties in these composites, while also ensuring the longevity of the armor materials. Ballistic tests conducted to evaluate the effectiveness of ceramic armor play an important role in understanding the real performance of these materials. However, the factors affecting the ballistic performance of ceramic armor are quite complex, and the success of the armor system emerges when these factors come together. Therefore, not only the hardness or fracture strength of the material, but also the fracture behavior of the material, the distribution of particles, and the holistic structure of the armor system should be considered [64], [65]. In the ballistic tests conducted, the performance of the material is measured against projects tested at different speeds and energy levels [66]. During these tests, how ceramic armors manage processes such as breaking, erosion, and deformation is carefully analyzed. The better performance of boron and boron derivatives compared to other ceramic materials makes them more effective, especially against high-speed projects. This feature will allow boron derivatives to find wider use in future armor systems [67].

2.5. Boron and its Use in the Rocket Industry

Boron is considered an important component in the design and performance of rocket propulsion systems [68]. Rocket engines have to produce a tremendous amount of energy to move at high speeds and carry loads, and the materials used to impart this energy have to be high-performance. Boron-based alloys present an incredibly effective answer to meet these requirements [69]. These alloys provide added value to rocket propulsion systems thanks to the chemical and physical properties of boron [70]. Boron compounds are good energy efficient, especially when rocket fuel is utilized. The most common application of boron compounds is the incorporation of compounds such as boron carbide (B_4C) and boron oxide (B_2O_3) into rocket fuel mixtures [71]. The high-energy thermal reactions released during the combustion reactions of these compounds allow the rocket engine to operate more efficiently [72]. In addition to this, the gases released due to these burning reactions of boron compounds impart the propulsion to accelerate the rocket and cover distant distances. This process plays an important role in achieving high thrust and low mass goals, which are specifically essential in space flights [73]. Boron alloys also stand out in their chemical stability and heat resistance at high levels of temperature and pressure. The environment of rocket engines is subjected to extreme heat and high pressures [74]. Boron alloys minimize material wear by retaining their structures in these environments. Boron also tends to enhance hardness and wear resistance in these alloys so that rocket engines become stronger [75]. Therefore, boron alloys improve energy efficiency and safety by improving the design life of rockets [76]. In addition, boron-containing compounds help reduce the total weight of rockets with their low density compared to other elements, which provides more carrying capacity [77].

This boron application in rocketry is an important dimension that boosts the efficiency and safety of rockets, especially in space exploration and the defense industry. These uses are not only a result of technological innovation but also because boron is a versatile element. Boron enables sustainable technology through the improvement of not only material efficiency but also environmental sustainability in rocket engineering [78].

2.6. Boron in Aerospace Applications

Boron is utilized as a very valuable material component in aerospace engineering, especially to meet structural strength and lightness requirements [79]. Aerospace structures like spacecraft, aircraft, and others are subjected to very harsh conditions when moving at high speeds or leaving the atmosphere. These kinds of conditions require maximizing material strength, lightness, and aerodynamic properties while in flight. Boron-based materials offer unique properties to meet these requirements [80].

Boron filaments exhibit very high specific strength and strength properties, especially when combined with composite materials such as carbon fiber-reinforced plastics (CFRP). These materials are used in aircraft wings, fuselage structures, and other critical components, allowing vehicles to reduce weight and increase durability [81]. Boron integrated into carbon fiber-reinforced plastics strengthens the structural integrity of the material and also provides resistance to thermal shock. This is a great advantage, especially for spacecraft and fast-moving aircraft, since vehicles are constantly exposed to such conditions [81]. Another advantage of the use of boron in aviation and space technologies is the high thermal conductivity and thermal resistance properties of the materials. Spacecraft are exposed to extreme temperature differences and vacuum conditions outside the atmosphere. Such environments require the materials used to be resistant to high temperatures [82]. Composites based on boron possess great resistance to these extremes, which allows for space flights to be conducted more efficiently and safely. Boron is also typically pointed out in these materials for its ability to absorb thermal shock; this allows airplanes and rockets to maintain their structural integrity [83]. Boron-based materials have also been found to be a worthy source of development for defense and space, as well as civil aviation due to their lightness and durability. In the construction of modern technology aircraft, boron-reinforced composites allow aircraft to travel longer distances while using less fuel. The cost of boron-based materials to the environment is also low, presenting a highly convenient benefit for green aviation technology [84].

Furthermore, boron is used as an important material in stealth technologies, especially in radar detection and reducing electromagnetic traceability [85]. Stealth technology is a technique developed to make military vehicles less visible to radar, infrared, and other detection systems [86]. Boron carbide significantly reduces the visibility of stealth aircraft and missiles with its ability to absorb radar waves [87]. This is less likely to be detected by enemy radars on military vehicles and hence more strategically advantageous when it comes to evading attacks. The boron carbide materials are used with materials that are typically implemented on the exteriors of stealth aircraft and missiles. Since the materials absorb, not reflect, radar waves, they offer traceability at different frequencies of the electromagnetic spectrum to a low degree [88]. In addition to this, the materials are highly resistant and abrasive, which allows for the outer layer of military machinery to withstand attacks for a very long time. These materials improve the pace and agility of stealth aircraft and allow the machines to detect fewer times and perform their task more effectively [89]. The use of boron carbide in stealth technology not only reduces radar visibility but also has high thermal shock and aerodynamic heating resistance at high speeds. This is a very critical factor, especially for aircraft and missiles that fly at high speeds. Boron also allows these materials to control airflow, which improves flight stability and aerodynamics [90]. The application of boron in stealth technology is central to military strategy formulation and security system upgrades. The enhanced effectiveness of stealth aircraft and missiles increases the rate of success of military operations and serves as an asset in the attainment of superiority on the ground [91].

3. Future Perspective of Boron and Boron Derivatives in the Defense Industry

The defense industry is an industry where the latest technologies are utilized at the most advanced level and national security policies are made. The defense industry consists of challenging applications requiring high-performance materials and compounds. Boron and boron derivatives have emerged as a prominent class of materials in the defense industry during the last decade. Thanks to its thermal, mechanical, and chemical characteristics, boron has found application in engine components, armor steel, high-temperature coating, and most especially to enhance strategic defense gear's lifespan [92].

In the defense industry, armor material research is important for military vehicles and personal protective equipment. Boron and boron compounds have properties that improve the mechanical properties of armor materials, improve the lightness of the material, and improve its carrying capacity. These materials are among the important components used in the construction of ballistic armors [3], [93]. Boron carbide (B_4C) is typically utilized in armor manufacturing due to its abrasiveness and hardness. Boron carbide has good durability against metal surfaces, especially in the case of high-velocity bullets and fragments of shrapnel, and thus improves the ballistic protective performance of armor materials [94]. The second major advantage of boron derivatives in the military field is that they increase the lightness of armor materials and improve the mobility of armored military vehicles. Heavy and bulky conventional armor materials would harm the speed and mileage of military vehicles [95]. Boron derivatives improve the hardness of armor in addition to increasing the weight optimization of the material. This is of great advantage for future military ships, aircraft, and vehicles [3], [72], [93]–[95].

However, many critical systems in the defense industry operate in extreme temperature conditions. Military equipment that requires high performance, such as aircraft, rockets, missiles, and gas turbine engines, require high-temperature resistance in their parts and engines. Boron derivatives play a crucial role in increasing the temperature resistance of the materials used in such systems [96]. Compounds of boron, when applied as coatings on metal surfaces at elevated temperatures, reduce the risks of oxidation and corrosion, thus ensuring the longevity of engine components. Borate coatings are significant in engines that operate under high-temperature conditions, especially in the defense industry. Borate coatings prevent oxidation and wear of materials caused by elevated temperatures in engines like gas turbines and rocket engines. These coatings minimize the expansion and deformation that occur on metal surfaces due to temperature increases, allowing engines to operate more effectively [97] [98]. Other than this, these coatings prevent loss of performance by thermal fatigue in high-temperature exposed metal components. Additionally, in defense applications, equipment must withstand rigorous environmental conditions and should not be plagued by loss of performance with constant usage [99]. Boron derivatives are also used extensively as coating materials for improving the wear resistance of the metal surface. Borate coatings also increase the life of the materials by preventing metal wear, especially in high-performance systems such as military vehicles, aircraft, and ships. The coatings lower damage caused by wear and friction, especially on metal surfaces [100]. For example, boron coatings reduce friction on metal surfaces used in aircraft engine and vehicle body components, thus allowing such components to move with ease for longer periods. Additionally, borate coatings harden the surface of the metal, making it wear-resistant against high-speed moving parts and bullets [101]. This property is specifically significant for the defense industry as armored vehicles, engines, and other defense hardware are likely to be exposed to high-speed rotating parts and hard-edged materials. Boron carbide coatings find a lot of use in the defense industry as an extremely hard substance with high wear and corrosion resistance [102]. Boron carbide is utilized in machines running at high temperature and pressure conditions and is proved to function properly even in the most extreme atmospheric conditions. Boron carbide is used in missile defense and aircraft engines and minimizes damage due to overheat and wear and tear in armored vehicles [103].

The use of boron and boron derivatives in the defense industry is not only limited to the development of existing technologies but is also shaping up to form the basic components of future strategic defense systems. These materials offer significant advantages in terms of both cost-effectiveness and performance, increasing the durability of military equipment and reinforcing superiority on the battlefield [104]. The defense industry can develop more efficient, durable, and lightweight defense systems by taking advantage of the properties of boron derivatives. This could be a significant turning point in the evolution of war technologies [105].

However, the use of boron derivatives in the defense industry can also transform military strategy and security policies. The integration of boron derivatives into developing technologies will allow countries to increase their independence and competitive advantage in the defense industry. The integration of boron and boron derivatives in future military systems will be a major step toward sustainability and efficiency in the defense industry. In this context, the future of boron and boron compounds in the defense industry will make significant contributions to the development of both military power and technology [106].

4. Conclusion

Boron and boron-derived compounds are of strategic importance for the defense industry thanks to their superior physicochemical properties such as high hardness, low density, thermal stability, and chemical resistance. Boron carbide, boron nitride, and boron-based composite materials are widely preferred in areas such as ballistic protection systems, armor applications, and lightweight and durable structural components. Considering the need for weight reduction and increased mobility and speed in modern warfare technologies, boron-based materials offer a critical solution. In addition, boron compounds, which act as neutron absorbers in nuclear defense technologies, play important roles in both weapon systems and reactor safety.

This strategic potential of boron makes it indispensable not only for military applications but also for sustainable materials engineering approaches in the defense industry. For countries rich in boron reserves, such as Turkey, this creates not only an economic but also a geopolitical advantage. In the future, boron is expected to be used more widely in the development of more functional, lightweight, and high-performance materials for the defense industry. In this context, it is of great importance to encourage multidisciplinary R&D studies that will enable the integration of boron-based materials into advanced technology.

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Author Contribution

M.B. created the conceptual framework of the study, conducted the literature review, wrote the first draft of the article contributed to the data collection processes, prepared the figures and tables, and actively participated in the writing and editing process.

R.B. created the conceptual framework of the study, conducted the literature review, prepared the figures and tables, and actively participated in the writing and editing process.

G.K., provided general academic direction of the study, scientific content verification, and critical feedback.

F.S. provided consultancy in the process of topic selection, and academic contribution to the interpretation of the results, and supported the final approval of the manuscript.

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