

A Comprehensive Review of Aluminium – Boron Carbide Matrix Composites

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Abstract

Composite materials are playing effective role in the development of automotives and aeronautical structural parts. Due to its flexibility and damping qualities and its easy approach of study and development, number of investigation and researches nowadays increases a lot. In this study, basics about Metal matrix composites with aluminium base are briefed. The nature and properties of boron carbide is also discussed effectively. Among many processing technique of AMC's, a best adoptive technique of microwave sintering methodology for Al-B₄C is discussed.

Keywords: *Microwave sintering, Boron Carbide, Aluminium matrix Composites, Ceramics.*

I. INTRODUCTION

The Performance of Aluminum matrix composites is mostly dependant on selecting the right combination of reinforcing materials since some of the processing parameters are associated with the reinforcing particulates.

Current interest in the development of materials that have good strength to weight ratio suitable for automobile application where fuel economy with improved engine performance becoming more critical.

Metal matrix composites offers tailored property combination required in a wide range of engineering applications: includes,

- 1) High specific strength
- 2) Low co-efficient thermal expansion
- 3) High thermal resistance
- 4) Good damping capacities
- 5) Superior wear resistance
- 6) High specific stiffness
- 7) Satisfactory level of corrosion resistance

II. CERAMICS IN MMC

MMC are basically metallic alloys reinforced with mostly ceramic materials.

The common metallic alloys utilized are alloys of light metals (Al, Mg & Ti). However, other metallic alloys like zinc (Zn), Copper (Cu) and stainless steel have been used.

A different approach has been adopted to improve the performance of discontinuous reinforced MMC. It involves the development of MMC using two or more reinforcing materials. This approach given room for possible reduction of cost coupled with property optimization in MMC.

The final properties of the hybrid reinforcement depend on individual properties of the reinforcement selected and the matrix alloy. Most of the parameters put into consideration during the design of AMC

are linked with the reinforcing materials. A few of such parameters are type, size, modulus of elasticity, hardness, distribution in the matrix among others.

Combination of reinforcement used in synthesis of hybrid AMC is mainly stick with two synthetic ceramic materials.

Silicon carbide (SiC), Alumina (Al₂O₃), Boron Carbide (B₄C), tungsten Carbide (WC), Graphite (Gr), Carbon nanotube (CNT), and Silica (SiO₂), Titanium Carbide (TiC), Titanium Bromide (TiB₂) are some of the synthetic ceramic particulate that has been used but silicon carbide and alumina are mostly utilized compared to other synthetic reinforcing particulates.

III. SIGNIFICANCE OF CERAMICS IN MMC

The introduction of a ceramic material into a MM produce a composite material that results in an attractive combination of physical and mechanical properties which cannot be obtained with monolithic alloys. Addition of hard reinforcements such as silicon carbide, Alumina and titanium carbide improves hardness, strength and wear of the composites [1,2,3,4]. Conventional AMC reinforced with SiC or

Al₂O₃ have shown improved strength and specific stiffness over the monolithic alloys but this occurs at the expense of ductility and fracture toughness.

Ductility and fracture toughness are important material properties that are necessary for preventing failure under in service or shock load applications. Graphite and Boron Carbide have been used alongside with SiC or Al₂O₃ to optimize the performance of AMC's.

The hardness and wear resistance of the hybrid composites were superior to that of the matrix material. Furthermore hardness of the composites containing SiC and Al₂O₃ was higher than that of the composites with SiC and Gr due to the combined pinning effect of SiC and Al₂O₃ and the higher hardness of Al₂O₃ to that of the Gr.

However, composite containing alumina despite its hardness has lower wear resistance to that of the composites containing Gr: Because Gr exhibits higher solid lubricating effect than alumina. AMC posses high load bearing capacity due to SiC reinforcement.

Alumina when hybrid with BN will result good solid lubricating effect like graphite and attains hexagonal closed packed structure [34,35].

Hybrid composites containing mica and SiC as reinforcements have superior hardness, tensile strength and wear resistance than the single reinforced silicon carbide aluminium composites. Here, AMC reinforced with 10 wt% SiC, mica added here was 6wt% in step of 3. [36] Due to the poor stirring and uneven distribution of the reinforcements in the matrix can create lacking in properties of tensile strength and flexural of reinforced AMC. Sometimes unreinforced alloy can have higher tensile strength and superior flexural properties than the hybrid counterparts. [37]

The hybrid composites had superior mechanical properties than the single reinforced Al/5 wt% SiC composite with Al/5wt% SiC/10wt% Gr having the highest strength and wear resistance. Here composite elements are in nano form. [38] Load bearing capacities and pinning effect of hard ceramic particulates and the solid lubricating effect posses by selected reinforcement such as graphite, alumina and boron nitride.

V. BORON CARBIDE - OVERVIEW

Boron Carbide is one of the hardest materials known, ranking third behind diamond and cubic boron nitride. It is the hardest material produced in tonnage quantities. Originally discovered in mid 19th century as a by-product in the production of metal borides, boron carbide was only studied in detail since 1930. Boron carbide powder is mainly produced by reacting carbon with B₂O₃ in an electric arc furnace, through carbo thermal reduction or by gas phase reactions.

For commercial use B₄C powders usually need to be milled and purified to remove metallic impurities. In common with other non-oxide materials boron carbide is difficult to sinter to full density, with hot pressing or sinter HIP being required to achieve greater than 95% of theoretical density. Even using these techniques, in order to achieve sintering at realistic temperatures (e.g. 1900 - 2200°C), small quantities of dopants such as fine carbon, or silicon carbide are usually required. As an alternative, B₄C can be formed as a coating

on a suitable substrate by vapour phase reaction techniques e.g. using boron halides or di-borane with methane or another chemical carbon source. (Web Article)

Key Properties

Boron Carbide is characterized by its:

- 1) Extreme hardness
- 2) Difficult to sinter to high relative densities without the use of sintering aids.
- 3) Low density
- 4) Good chemical resistance
- 5) Good nuclear properties
- 6) Low density

See table: 1

Due to its high hardness, boron carbide powder is used as an abrasive in polishing and lapping applications, and also as a loose abrasive in cutting applications such as water jet cutting. It can also be used for dressing diamond tools. The extreme hardness of boron carbide gives it excellent wear and abrasion resistance and as a consequence it finds application as nozzles for slurry pumping, grit blasting and in water jet cutters.

Table: 1

PROPERTY	
Density (g.cm ⁻³)	2.52

Melting Point (°C)	2445
Hardness (Knoop 100g) (kg.mm ⁻²)	2900-3580
Fracture Toughness (MPa.m ^{-½})	2.9 - 3.7
Young's Modulus (GPa)	450 - 470
Electrical Conductivity (at 25°C) (S)	140
Thermal Conductivity (at 25°C) (W/m.K)	30 - 42
Thermal Expansion Co-eff. x10 ⁻⁶ (°C)	5
Thermal neutron capture cross section (barn)	600

Its ability to absorb neutrons without forming long lived radio-nuclides make the material attractive as an absorbent for neutron radiation arising in nuclear power plants. Nuclear applications of boron carbide include shielding, and control rod and shut down pellets. Boron carbide, in conjunction with other materials also finds use as ballistic armour (including body or personal armour) where the combination of high hardness, high elastic modulus, and low density give the material an exceptionally high specific stopping power to defeat high velocity projectiles. Other applications include ceramic tooling dies, precision toll parts, evaporating boats for materials testing and mortars and pestles.[web]

VI ALUMINIUM –OVERVIEW

Aluminium is the world's most abundant metal and does the third most common

element comprise 8% of the earth's crust. The versatility of aluminium makes it the most widely used metal after steel. Aluminium is derived from the mineral bauxite. Bauxite is converted to aluminium oxide (alumina) via the Bayer Process. The alumina is then converted to aluminium metal using electrolytic cells and the Hall-Heroult Process. Worldwide demand for aluminium is around 29 million tons per year. About 22 million tons is new aluminium and 7 million tons is recycled aluminium scrap. The use of recycled aluminium is economically and environmentally compelling. It takes 14,000 kWh to produce 1 tonne of new aluminium. Conversely it takes only 5% of this to remelt and recycle one tonne of aluminium. There is no difference in quality between virgin and recycled aluminium alloys. Pure aluminium is soft, ductile, corrosion

resistant and has a high electrical conductivity. It is widely used for foil and conductor cables, but alloying with other elements is necessary to provide the higher strengths needed for other applications. Aluminium is one of the lightest engineering metals, having strength to weight ratio superior to steel.

By utilising various combinations of its advantageous properties such as strength, lightness, corrosion resistance, recyclability and formability, aluminium is being employed in an ever-increasing number of applications. This array of products ranges from structural materials through to thin packaging foils.

Key Properties

Property	Value
Atomic Number	13
Atomic Weight (g/mol)	26.98
Valency	3
Crystal Structure	FCC
Melting Point (°C)	660.2
Boiling Point (°C)	2480
Mean Specific Heat (0-100°C) (cal/g.°C)	0.219
Thermal Conductivity (0-100°C) (cal/cms. °C)	0.57
Co-Efficient of Linear Expansion (0-100°C) ($\times 10^{-6}/^{\circ}\text{C}$)	23.5
Electrical Resistivity at 20°C ($\Omega\cdot\text{cm}$)	2.69
Density (g/cm^3)	2.6898
Modulus of Elasticity (GPa)	68.3
Poissons Ratio	0.34

Aluminium can be severely deformed without failure. This allows aluminium to be formed by rolling, extruding, drawing, machining and other mechanical processes. It can also be cast to a high tolerance.

Alloying, cold working and heat-treating can all be utilised to tailor the properties of aluminium. The tensile strength of pure aluminium is around 90 MPa but this can be

increased to over 690 MPa for some heat-treatable alloys.

Aluminium has a density around one third that of steel or copper making it one of the lightest commercially available metals. The resultant high strength to weight ratio makes it an important structural material allowing increased payloads or fuel savings for transport industries in particular. Pure aluminium doesn't have a high tensile strength. However, the addition of alloying elements like manganese, silicon, copper and magnesium can increase the strength properties of aluminium and produce an alloy with properties tailored to particular applications.

Aluminium is well suited to cold environments. It has the advantage over steel in that its' tensile strength increases with decreasing temperature while retaining its toughness. Steel on the other hand becomes brittle at low temperatures. When exposed to air, a layer of aluminium oxide forms almost instantaneously on the surface of aluminium. This layer has excellent resistance to corrosion. It is fairly resistant to most acids but less resistant to alkalis. The thermal conductivity of aluminium is about three times greater than that of steel.

This makes aluminium an important material for both cooling and heating applications such as heat-exchangers. Combined with it being non-toxic this property means aluminium is used extensively in cooking utensils and kitchenware.

Along with copper, aluminium has an electrical conductivity high enough for use as an electrical conductor. Although the conductivity of the commonly used conducting alloy (1350) is only around 62% of annealed copper, it is only one third the weight and can therefore conduct twice as much electricity when compared with copper of the same weight. From UV to infra-red, aluminium is an excellent reflector of radiant energy. Visible light reflectivity of around 80% means it is widely used in light fixtures. The same properties of reflectivity makes aluminium ideal as an insulating material to protect against the sun's rays in summer, while insulating against heat loss in winter.

VII Al-B4C MATRIX COMPOSITES

Monolithic Boron Carbide has high brittleness due to high strain rate. Combining the B4C with a metal can mitigate the problem associated with

brittleness. By far, the most popular metal used in joining B4C for this purpose is aluminium. It wets B4C well at elevated temperature. Molten aluminium has been shown to form a variety of binary and tertiary phases when in contact with B4C such as Al₃BC, AlB₁₀ and Al₄C₃. Among these phases, Al₃BC is the mostly common observed phase. [13, 14]

The sintering of composite materials by microwave processing has been known to reduce heating temperature and time to lead to fine microstructure and improved mechanical properties. The B4C react strongly with liquid aluminium resulting in a variety of compounds, including 1. Al₃BC 2. AlB₂₄C₄(AlB₁₀) 3. Al₈B₄C₇ 4. Al₃B₄₈C₂(b-AlB₁₂), 5. AlB₂ 6. AlB₁₂C₁₂ 6. AlB₄₈C₂ 7. Al₄C₃ and (a-AlB₁₂.7). [23]

a) Microwave Sintering

Microwave energy has been in use for a variety of applications for over 50 years. Some of the early applications include communication, navigation and drying of food items. At present, industrial uses of microwaves include wood processing, vulcanization of rubber, meat tempering, and medical therapy. In the past two

decades, the remarkable success of domestic microwave ovens has revolutionized home cooking. The use of microwaves in ceramic processing is a relatively recent development. They can be applied effectively and efficiently to heat and sinter ceramic objects.

The most recent development in microwave applications is in sintering of metal powders, a surprising application, in view of the fact that bulk metals reflect microwaves. However, reflection by a metal occurs only if it is in a solid, nonporous form and is exposed to microwaves at room temperature. Metal in the form of powder will absorb microwaves at room temperature and will be heated very effectively and rapidly. This technology can be used to sinter various powder metal components, and has produced useful products ranging from small cylinders, rods, gears and automotive components in 30-90 min. Microwave heating and sintering is fundamentally different from the conventional sintering, which involves radiant/resistance heating followed by transfer of thermal energy via conduction to the inside of the body being processed.

Microwave heating is a volumetric heating involving conversion of electromagnetic energy into thermal energy, which is instantaneous, rapid and highly efficient.

The microwave part of the electromagnetic spectrum corresponds to frequencies between 300 MHz and 300 GHz. However, most research and industrial activities involve microwaves only at 2.45 GHz and 915 MHz frequencies. Based on their microwave interaction, most materials can be classified into one of three categories - opaque, transparent and absorbers. Bulk metals are opaque to microwave and are good reflectors - this property is used in radar detection.

However, powdered metals are very good absorbers of microwaves and heat up effectively, with heating rates as high as 100°C min⁻¹. Most other materials are either transparent or absorb microwaves to varying degrees at ambient temperature. The degree of microwave absorption, and consequently of heating, changes dramatically with temperature.

The use of microwave energy for materials processing has major potential and real

advantages over conventional heating. These include:

- 1) Time and energy savings,
- 2) Rapid heating rates,
- 3) Considerably reduced processing time and temperature,
- 4) Fine microstructures and hence improved mechanical properties and better product performance,
- 5) 5.Lower environmental impact.

Until recently, microwave heating has been applied to sinter only oxide ceramics and semi-metals like carbides and nitrides. However, our research reveals that in powdered form, virtually all metals, alloys, and intermetallics will couple and heat efficiently and effectively in a microwave field, and their green parts will produce highly sintered bodies with improved mechanical properties. For example, in exploratory experiments, two common commercial steel compositions tried, namely Fe-Ni-C (FN208) and Fe-Cu-C (FC208). These formed highly sintered bodies in a total cycle time of about 90 min at temperature range of 1100-1300°C with a soaking time of 5-30 min in forming gas (a mixture of N₂ and H₂) atmosphere.

Mechanical properties such as the modulus of rupture (MOR) and hardness of microwave processed samples were significantly higher than the conventional samples - in the case of FN208, the MOR was 60% higher. The densities of microwave processed samples were close to the theoretical densities, and the net shape of the green body was preserved without significant dimensional changes.

Many commercial powder-metal components of various alloy compositions, including iron and steel, copper, aluminum, nickel, molybdenum, cobalt, tungsten, tungsten carbide, tin, and their alloys have been sintered using microwaves, producing essentially fully dense bodies. Figure 1 illustrates some of the metallurgical parts processed using microwave technology. The biggest commercial steel component that has been fully sintered in our system so far is an automotive gear of 10 cm in diameter and about 2.5 cm in height.



Figure1. Metallic parts produced by microwave sintering such as gears cylinders, rods and discs.

A typical microwave sintering apparatus operates at a 2.45 GHz frequency with power output in the range of 1-6 kW. The sintering chamber consists of ceramic insulation housing (batch system) or an alumina tube insulated with ceramic insulation from outside, **figure 2**.

The primary function of the insulation is to preserve the heat generated in the work piece. The temperatures are monitored by optical pyrometers, IR sensors and/or sheathed thermocouples placed close to the surface of the sample. The system is equipped with appropriate equipment to provide the desired sintering atmosphere, such as H₂, N₂, Ar, etc, and is capable of achieving temperatures up to 1600°C.

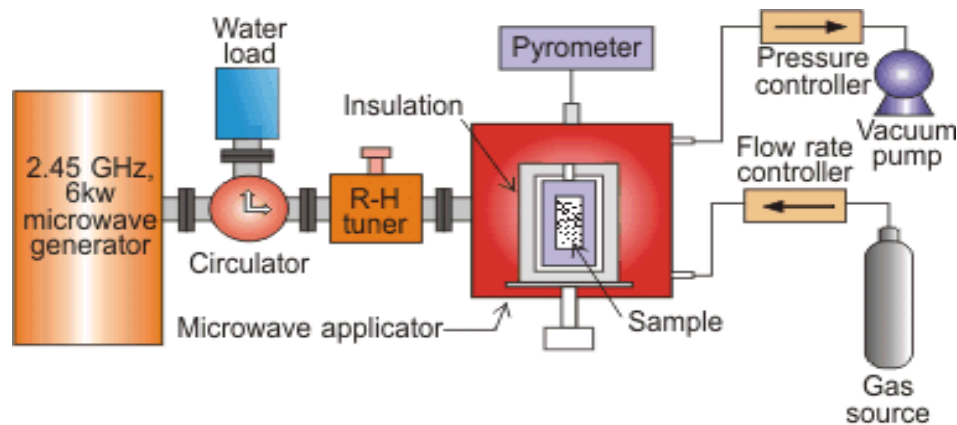


Figure 2. Schematic diagram of a microwave sintering furnace.

The technology can be easily commercialized by scaling up the existing microwave system or designing a continuous system capable of sintering parts of various shapes and sizes. The implications of microwave sintering of metals are obvious in the field of powder metal technology. Metal powders are used in a diverse range of products and applications in various industries, including the automotive industry, aerospace, and heavy machinery.

The challenging demands for new and improved processes and materials of high integrity for advanced engineering applications require innovation and new technologies. Finer microstructures and near-theoretical densities in special powder metal components are still elusive and

widely desired. Increasing cost is also a concern of the industry. Microwave processing offers a new method to meet these demands of producing fine microstructures and better properties, and potentially at lower cost.

There are two main reasons why the microwave process yields better mechanical properties, especially in the case of powder metals - it produces a finer grain size, and the shape of the porosity, if any, is quite different than in a conventional part. In microwave-processed powder metal components, we have observed round-edged porosities producing higher ductility and toughness.

So far, there has been little effort devoted to understanding the mechanisms and the

science behind microwave sintering of metals. However, it is obvious that the microwave-metal interactions are more complex than those working actively in the field had expected. There are many factors that contribute significantly to the total microwave heating of powdered metals.

The sample size and shape, the distribution of the microwave energy inside the cavity, and the magnetic field of the electromagnetic radiation are all important in the heating and sintering of powder metals. This research is just at the early stages, and it will be a long time before the exact mechanisms are elucidated.

b) Experimental Procedure

B₄C (Aldrich-378100) and aluminium (1056-merck) powders were used as the starting materials and cobalt powder (99.8%

purity and 5 micrometer mean particle size) was used as an additive. Samples are given in **table:2**

The mixing of powders presented above can be carried out using spex instrument (8000 D,Mixer mill).The mixed powders are compacted to prepare the bar shape samples with the dimension of 25mm X 5mm X 5mm at 250 Mpa using a uniaxial press. The compression strength test samples can be fabricated using a hydraulic press type to obtain cylindrical performs with a diameter of 10 mm and height of 8mm.The sintering of those samples will be carried out using a microwave furnace (900W and 2.45 GHz),which monitored temperature using an optical pyrometer at 650⁰C,750⁰C,850⁰C,950⁰C without soaking time in a graphite bed.

Table: 2

Category	Al (wt%)	B ₄ C(wt%)	Co(wt%)
A	90	10	0
B	89	10	1
C	83.5	15	1.5
D	78	20	2

The bulk density of sintered samples can be measured using the Archimedes principle. The three point bending and compressive strength measurements can be examined by santam-STM 20. For bending and compressive strength tests, five or three specimen were used. X ray diffraction analyses can be performed to identify the phases present in the Al-B₄C composites. Here Philips (30KV and 25 mA) diffractometer system with CuK radiation of wavelength 1.5405 Angstrom can be used. Micro hardness tester (MKV-h21 , Akashi) under a load of 1 Kgf for 15 sec are used to determine Vickers micro hardness values of the sintered samples. Atleast ten successive indentation were performed for each sample.

VII. CONCLUSION

In this work a detailed study on methodology of Microwave sintering process has been considered. Though there are many processing technique like friction stir casting, mechanical alloying and novel mixing process ,this microwave sintering process posses importance due to its simplicity and well output. In this study, some aspects in AMC composites and its evolution with ceramic particles has been done. This study leads to analyze and understand the importance of microwave

sintering process through the development of practical model. And the importance of boron carbide in AMC has been briefed.

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