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(Review Article)

Aluminum boron carbide metal matrix composites for fatigue-based applications: A comprehensive review

Arun C Dixit [1, *], Harshavardhan B [2] and Ashok BC [1]

[1] *Department of Mechanical Engineering, Vidyavardhaka College of Engineering, Mysuru, India.*
[2] *Department of Mechanical Engineering, The National Institute of Engineering, Mysuru, India.*

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Abstract

Metal matrix composites (MMCs), known for their low density and superior stiffness, have gained significant attention in various load bearing and fatigue-prone applications. These composites offer distinct advantages over traditional monolithic metals, including enhanced mechanical and tribological properties, making them prime candidates for lightweight structural applications. Among ceramic reinforcements, boron carbide stands out due to its lower density, high elastic modulus, excellent refractoriness, and superior hardness, positioning it as an ideal reinforcement material. This review delves into the processing techniques, material properties, and microstructural characteristics of boron carbide-reinforced MMCs, with a focus on aluminum LM6 alloy as the matrix. Additionally, the paper explores the latest advancements and emerging opportunities for employing these composites in fatigue-critical applications, highlighting their potential to revolutionize industries requiring high performance and durability under repeated loading conditions.

Keywords: Aluminum LM6; Boron Carbide; Stir casting; Fatigue life; Failure; Microstructure

1. Introduction

Composites, plastics and ceramics are the predominantly incorporated materials in many engineering applications from the last decade. The concept behind the use of metal matrix composites components in the automotive, aerospace, farming, and defense sectors is focused on weight reduction criteria and in search of enhanced material competence and performance. Customers are constraining the energy allied industry to gradually limit fuel economy standards, demanding better comfort and safety. Automobile component manufacturers are looking towards reduction in weight and effective models to meet these obligations. In long-term applications where reduced weight is an important feature, aluminum alloy metal matrix composites with high specific rigidity and high strength can be employed [1], [2], [3].

Enhancement of mechanical properties depends primarily on the homogeneous dispersion and the interfacial reaction (to form new compounds) amidst the reinforcement particles and matrix. Ceramic reinforcements such as silicon carbide, boron carbide, alumina oxide, titanium carbide, Fly ash and marble dust have been developed and characterized for many relevant purposes [4], [5], [6].

In addition to advancements in metal matrix composites, the integration of sustainable technologies has gained momentum in various engineering sectors. With the growing focus on reducing environmental impact, there is a shift towards incorporating greener solutions in both material and energy use. For example, green hydrogen has emerged as a promising alternative in the energy sector, offering a clean and efficient fuel option for industries such as transportation and aerospace. The development of lightweight composites, such as aluminum-based metal matrix composites, aligns with this trend by enhancing fuel efficiency through weight reduction. Combining these materials

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[*] Corresponding author: Arun C Dixit

with green hydrogen technologies can further optimize performance in high-demand sectors, supporting the global shift towards sustainability [7], [8], [9], [10], [11], [12].

This review attempts to review the research conducted on diverse aluminum alloys and boron carbide reinforcement. The effect and influence of matrix and reinforcement on overall performance of the composite and their probable applications will also be discussed. Different categories of aluminum alloys (wrought and casted) will be considered to identify a better matrix material.

2. Materials - Matrix and Reinforcement

2.1. Matrix: Aluminum Alloys

Although numerous metallic alloy systems can serve as matrix materials, aluminum (Al) alloys have garnered the most attention due to their lower cost, reduced density, ability to undergo heat treatment, broad range of alloy variations, and ease of fabrication. These attributes make aluminum alloys particularly appealing for applications requiring lightweight and high-performance materials [13].

Forged aluminum alloys are classified using a numerical designation system (e.g., 1XXX, 2XXX, etc.), where the initial digit signifies the primary alloying element [14]. Table 1 provides an overview of these classifications, demonstrating how the alloying components influence the hardening mechanisms specific to each alloy family.

Table 1 Standard terminology of forged Al alloys

Alloy Designation	Detail
1XXX	99% Pure Aluminium
2XXX	Cu containing alloy
3XXX	Mn containing alloy
4XXX	Si containing alloy
5XXX	Mg containing alloy
6XXX	Mg and Si containing alloy
7XXX	Zn containing alloy
8XXX	Other alloys

There are also a varied variety of LM alloy applications in automotive brakes, power train, chassis and body construction. In automotive powertrain, aluminum castings have been used at most in pistons, then in cylinder heads, also in manifolds and transmissions. In chassis-based applications, composites are used for wheels attachments, wheel brackets, brake pads, suspensions, steering parts and in body panels. Aluminium is mostly used for body constructions, panels, closures and exterior attachments such as crossbeams, doors or bonnets. Recent advances reveal that weight of the body can be reduced by 30% of vehicle weight with the replacement of aluminum by steel. The cost and price stability is its biggest hindrance for this application. Based on the commercial purpose and applications LM series aluminum cast alloys are preferred than Designated wrought alloys [15], [16].

Commercially available Al-Si alloy i.e., LM6 having exceptional cast ability is considered to be proposed as a prominent matrix material in this review. The chemical constitution of the alloy Al-Si is shown in Table 2. In both corrosive and ordinary atmospheric situations LM6 displays outstanding opposition to corrosion.

Having exceptional fluidity, LM6 alloy is the best choice for small and large castings with thin sections and complicated shapes. The LM6 aluminum alloys are also the most malleable. This is a significant aspect formany marine applications, such as boat propellers, which need to function capably and have some ductility, without breaking, in severe situations. LM6 alloys are not easy to process/machine as a result of its high silicon percentage, and it demonstrates improved wear resistance compared to other Al-Si based alloys [17].

Table 2 Chemical constitution of Aluminum LM6 alloy

Alloy	Cu	Si	Mg	Zn	Fe	Mn	Ni	Sn	Pb	Ti	Al
LM6	0.1 max	10 to 13	0.1 max	0.1 max	0.1 max	0.5 max	0.1 max	0.05 max	0.1 max	0.2 max	Remainder

The mechanical properties of LM alloys are listed below in Table 3. The values presented are representative ranges for sand and chill cast test bars formed to the requirements of B.S.1490 and for 6 mm diameter die cast bars. From the Table 3, it can be appreciated that LM6 has highest percentage of elongation (in 50 mm), moderate hardness, average durability and excellent thermal conductivity. Through the addition of a proper/suitable reinforcement it is possible to further strengthen the alloy with respect to tensile stresses and young's modulus. There is an ample opportunity to improve dynamic and fatigue properties without much compromise in ductility [18]

Table 3 Mechanical properties of different Aluminum LM alloys

Alloy	**LM4**	**LM6**	**LM13**	**LM24**	**LM25**	**LM26**	**LM28**	**LM29**	**LM30**
Density (g/cm^3)	2.75	2.65	2.7	2.27	2.68	2.8	2.68	2.65	2.73
Thermal conductivity (W/mK)	0.29	0.34	0.28	0.23	0.36	0.25	0.26-0.29	0.24-0.27	0.32
Tensile Stress (N/mm^2)	140-170	160-190	170-200	180	130-150	210	170	120	275
% Elongation in 50 mm	2-3	5	0.5	1.5	2	1	0.5	0.5	1
Hardness (BHN)	65-80	50-55	100-150	85	55-65	90-120	90-130	100-140	170
Modulus of Elasticity (x10^3 N/mm^2)	71	71	73	71	71	82	88	82	82
Coeff. of Thermal Expansion (μm/m-°C)	21*e^4	20*e^4	19*e^4	21*e^4	22*e^4	21*e^4	175*e^4	165*e^4	18*e^4

It is observed that most of the researchers have prominently incorporated Al 6061, Al 2024, Al 7075, LM25 and LM 26 in their research work. Though the properties and applications of LM6 alloys are prominent, their characterization data are scarce. It can be considered as a potential candidate as matrix material in metal matrix composites.

2.2. Reinforcement: Boron Carbide

Because of its prospective for substantial enhancement of mechanical and thermal properties, aluminum metal matrix reinforced by boron carbide particulates is the focus of review. Table 4 shows the properties of various reinforcements generally used in composites with discontinuously reinforced particulate metal matrix[19].

Table 4 Properties of various reinforcements

Ceramic	**Density (g/cm^3)**	**Elastic Modulus (Gpa)**	**Knoop Hardness**	**Compressive Strength (Mpa)**	**Thermal Conductivity (W/m·K)**	**Coefficient of Thermal Expansion (10e-6/K)**	**Specific Thermal Conductivity (W·m^2/kg·K)**
SiC	3.21	430	2480	2800	132	3.4	41.1
B_4C	2.52	450	2800	3000	29	5	11.5
Al_2O_3	3.92	350	2000	2500	32.6	6.8	8.3
TiC	4.93	345	2500	2500	20.5	7.4	4.2

B_4C density is found to be less than in comparison to available ceramic reinforcements, such as silicon carbide and aluminum oxide. Incorporating this reinforcement increases the matrix's rigidity and strength. It has exceptional toughness, excellent thermal stability, wettability, substantial chemical inertness and strong abrasiveproperties. It can be considered as an ideal candidate for strengthening aluminum-based composites.

2.3. Processing/fabrication of B_4C reinforced MMC

Metal matrix composites could be made-up by several different approaches. However two prominently used approaches are: liquid method (ex: stir casting) and solid or compacting method (ex: powder metallurgy) [20].

In-situ (processed internally in the matrix during the course of manufacture) and Ex – situ (reinforcement processed externally and added to matrix during the course of manufacture) are the two approaches for processing of metal matrix composites. Stir casting is an ex-situ method where certain calculated amount of processed reinforcement is added during the process. To obtain good casting intermittent stirring and temperature control are essential [21].

Stir casting has been considered here as the preferred method for review as it is economical and convenient. It was observed that B_4C needs to be preheated to achieve good wettability. Graphite crucible has been used to melt the material inside the furnace. It is also suggested to use degassing tablets to eliminate hydrogen diffused in molten matrix. Figure 1 shows the experimental set up a simple stir casting apparatus [22].

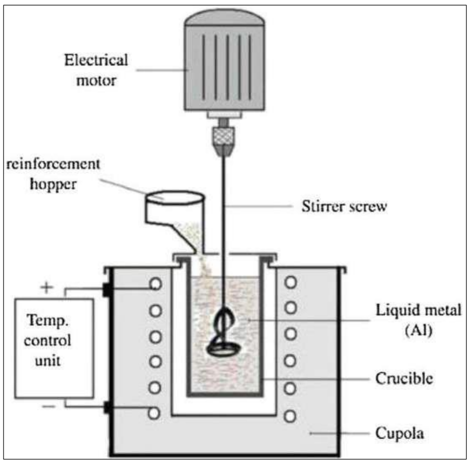

Figure 1 Working principle of Stir casting process

Uniform distribution, wettability of B_4C in matrix and solidification of the resulting composite are the main factors to be observed and controlled during the processing of the composite. Inclusions, porosity, voids and accidental chemical reactions should be avoided by regulating the process cautiously. Flaws or deficiencies suchas clustering (gathering), agglomeration (accumulation) and segregation (separation) will be the consequence of improper fabrication methodology leading to uneven distribution and reduced strength of the composite [23].

Several methods are suggested by many researchers to increase the wettability (ability of the matrix to wet the reinforcement particle). Processing of B_4C reinforced composites below 1100^0C is reported to be extremely crucial and challenging. Fluxes or additives such as K_2TiF_6 (Potassium hexafluorotitanate) and KCl-KF (potassium chloride-fluoride) are reported to be supplemented to boost wettability of boron carbide into Al matrix. Potassium hexafluorotitanate acts in two ways. Grain refinement and tough bond with aluminium metal is the effect of Titanate (Ti) component. Gas trapping in the melt can be shunned through Potassium and fluoride components. Apart from fluxes as described above, metals such as Magnesium, Titanium and Zirconia may also be added in combination or individually to enhance the properties of the resulting composite [24].

During processing, it is recommended to maintain melt temperature from 800 to 920^0C, stirring speed from 250 to 500 rpm and mould preheat temperature from 400 to 500 ^0C under inert atmosphere. This can be achieved byadministering argon gas into the melt or the usage of C_2Cl_6 (Hexacloroethane) to eliminate the hydrogen gas [25].

2.4. Mechanical properties of B_4C reinforced MMC

Matrix materials are usually weak, and their property needs to be improved to propose them for a suitable application. Reinforcements are combined with the matrix to augment the load bearing capacity and improve fracture properties. Thus, proper dispersal of reinforcement in the matrix is essential to obtain a composite without any defects. Method of integration, amount (wt.% or vol. %) and distribution of reinforcements in the matrix are the key parameters that influence the mechanical properties such as ultimate tensile strength, hardness, energy absorption, fracture toughness and compression strength [26], [27].

Increasing the amount of reinforcement up to a certain weight percentage lead to increased mechanicalproperties as it induces strength and makes the composite resistant to applied external stresses. Higher dislocation or displacement density of B_4C in the matrix and thus better dispersal can obtained as it is observed that the coefficient of thermal expansion between the matrix and the boron carbide particle is very high. This difference produces enough driving force for the B_4C particles to scatter thus avoiding agglomeration. This increases the load bearing capacity and also avoids the crack propagation. Restricted plastic flow during applied stresses is also reported to increase the compressive strength [28], [29].

Researchers have stated that with the decreasing inter-molecular distance (achieved by uniform dispersion),yield stress of the composite increases. The inter-molecular distances designated by 'λ' of B_4C reinforcement's values are recommended to be within 10 µm. At higher temperature, during processing, inter-metallic phases such as Aluminum diboride, Aluminum boride carbide and Aluminum carbide are formed because of the reaction between aluminum alloy and boron carbide. These phases increase the stress required for plastic deformation (flow stress) and thus slightly decreases the ductility of the composite. Therefore, enough care should be taken while processing at higher temperature as it leads to the composite with less ductility [30].

Many of the authors have described improved mechanical properties such as yield/ultimate tensile strength and hardness for 15 vol% of boron carbide reinforced metal matrix composites when compared to pure Al but ductility decreases by increasing the B4C reinforcement [24].

Since the density of Boron Carbide is lesser in comparison to the aluminium matrix, homogeneous dispersion during casting process will be difficult to achieve with large 25 volume of Boron Carbide. The abrasive nature of the ceramic phases generally causes rapid wear of materials. It is reported that it is advantageous to incorporate only a small volume fraction of reinforcing particles in the aluminium alloys to allow efficient machining of the composites [31].

2.5. Microstructure of Boron Carbide reinforced MMC

The microstructure is one of the most significant features that affect the physical properties of the metal/ alloy. Through microstructure, we can forecast the behavior and obtain the constituents of a component made of particular material. Microstructure is also significant while predicting the failure of a component under certain circumstances [32].

Microstructure of composites made-up by stir casting process can be completely characterized by X-Ray Diffraction (XRD), Optical Microscope, Scanning Electron Microscopy (SEM), Atomic Tunnel Microscopy (ATM), and Field Emission Scanning Electron Microscope (FESEM). A perfect representation about distribution of the particles, bonding among matrix-reinforcement and solid phases of two or more metallic items (intermetallic phase) of the composite can be evaluated through analysis of microstructure. Also, composites solidification mechanism during processing indicates a vital role in interpreting its microstructures. Because of particle pushing, B_4C particles are barred from the solid front and are trapped in the inter-dendrite (crystal with branches) region. This causes them to detach from the dendrite divisions into the materials as particle-free areas [33].

Certain factors affecting and impacting microstructure analysis include grain dimension of reinforcement particulates (micron meters), additional fluxes used and reinforcement weight percentage. From Fig. 2, it is evident that uniform dispersal can be obtained with reinforcements having grain size more than 20 µm. For particles of grain size less than 10µm agglomerations can be observed [34].

The quantity of flux used for uniform dispersal has also been found to be somewhat equal to the quantity of boron carbide reinforcement particulates and must be increased while using particulates with higher particle fractions (i.e. 15 wt. per cent) or smaller particle dimensions (< 10 µm) [35].

Several researchers have endorsed that the optimal amount of reinforcement must be up to 10% by either weight or volume percentage. Lesser amounts of reinforcement give rise to numerous particulate-free areas while higher amounts promote voids and growing locations for diverse void nucleation. In view of more particles grouping orclustering, the particles are bounded by surface gas layers and the blocked liquid metal flows [36].

2.6. Aluminum LM6-Boron Carbide composites: Opportunities

LM6 alloy stands out as a highly versatile casting alloy, known for its excellent casting properties, low density, and impressive ductility, making it a strong candidate as a matrix material in composite manufacturing. Stir casting, a cost-effective and straightforward method, further enhances its appeal for creating composites. When reinforced with boron carbide (B4C), which has a density lower than aluminum and offers outstanding physical properties, the composite's overall weight is significantly reduced, without compromising performance [37].

The addition of B4C to Al-LM6 alloy has been shown to enhance its mechanical properties, particularly by increasing its critical speed and resonance frequency. Despite the promising improvements observed in this combination, research on the specific behavior of Al-LM6/B4C composites remains limited. This presents an exciting opportunity for further exploration [38].

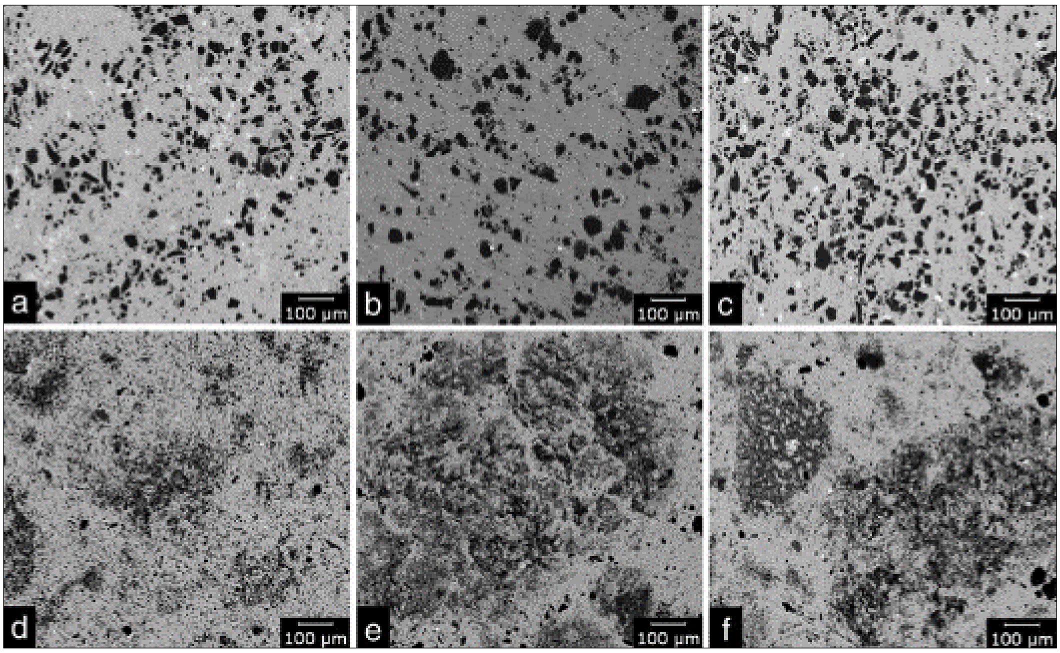

Figure 2 (a, b & c) indicating homogeneous distribution of B4C particles having grain size >20µm. (d, e& f) showing agglomeration of B4C particles having grain size <10 µm within the matrix

The increase in critical speed and resonance frequency offers a distinct advantage, especially in applications requiring high-speed rotation. The potential for weight reduction and increased performance makes this composite combination particularly attractive for use in high-performance applications such as formula racing cars, aircraft, and space engines, where the demand for higher safe operating speeds is ever-growing [39].

Notably, researchers have found that composite drive shafts made from these materials can replace traditional dual-member steel shafts, providing substantial benefits. The composite drive shafts exhibit reduced vibration, slower crack propagation, and enhanced fatigue strength. This highlights the immense potential of Al-LM6/B4C composites in fatigue-critical applications [40].

Given the widespread use of aluminum drive shafts in cars, trucks, and bicycles, incorporating Al-LM6 with B4C reinforcement can lead to significant reductions in weight, improved speed performance, and enhanced fatigue life, all while maintaining a simpler design. This combination represents a promising innovation for the next generation of lightweight, high-performance components.

3. Conclusion

This comprehensive review introduces a novel lightweight combination of aluminum LM6 alloy and boron carbide as matrix and reinforcement, respectively. LM6 offers low density, exceptional ductility, and excellent castability, while boron carbide, with its lower density and superior physical properties compared to aluminum, proves to be an ideal reinforcement material.

The review highlights the key challenges and observations related to using boron carbide as reinforcement across various alloys. It emphasizes that stir casting is a suitable processing method for achieving uniform dispersion and high-quality casting. For casting temperatures below 1100°C, the addition of fluxes is recommended to improve dispersion and avoid defects such as agglomeration and clustering. A boron carbide weight percentage of less than 10% is suggested to ensure optimal composite properties.

The findings related to processing, testing, and microstructure can be directly applied to the proposed LM6 and boron carbide composite. However, establishing a well-defined processing methodology is crucial to achieving consistent uniformity in dispersion. Additionally, thorough testing of the LM6/B4C composite across a range of mechanical properties—including tensile strength, hardness, wear resistance, and thermal performance—is essential to validate its potential.

The aluminum LM6 reinforced with boron carbide shows promising potential for fatigue-critical applications, particularly in automotive drive shafts and high-speed rotating machinery components. To fully explore its suitability for such applications, future research must focus on detailed fatigue, fracture, and durability studies. This will help establish a comprehensive data set and unlock new opportunities for using this composite in advanced engineering applications.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that there are no conflicts of interest related to this study.

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