Assessment of mechanical properties of LM13 aluminum alloy hybrid metal matrix composites

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Abstract
Aluminium LM13 alloy based hybrid particulate composites have been processed by adding boron carbide (B₄C) and titanium diboride (TiB₂) particles. The wt% of titanium diboride (TiB₂) is varied as 0, 3, 6, 9, 12, 15 and a constant 3 wt% of boron carbide is used to prepare the composites. Stir cast route is used to fabricate the composites. The microstructures of castings are examined using computer aided image analyzer. Vicker hardness, yield strength, ultimate tensile strength and energy absorbed by the composites are examined and reported. The results show that uniform dispersion of TiB₂ and B₄C reinforcement phases in Al LM13 alloy. Micro hardness of composites enhanced upto 36.6% when compared to Al alloy reinforced with 3 wt% of B₄C particles. Ultimate tensile strength of Al alloy is improved from 151 MPa to 192 MPa by reinforcing 15 wt% of titanium diboride particles. LM13 aluminium alloy hybrid particulate composites offers superior vicker hardness, yield strength, ultimate tensile strength and impact strength over LM13 aluminium alloy based single particle reinforced composites.

1. Introduction
Initially the matrix composites used graphite, boron, and ceramide fibres as reinforcements in 1960. The ability to create new property combinations and superior mechanical properties than the traditional engineering materials is the driving factor behind metal matrix composite (MMC) growth. The MMC has greater strength and rigidity, withstand at higher temperature fields and offers better wear properties. The quantity of scientific work done on MMC has increased by 150 percent in the previous 20 years, indicating a massive growth in development of MMC. The MMC comprised of discontinuous and continuous reinforcement such as continuous fibre, whiskers, particle which offers physical and mechanical properties in the monolithic alloy. Chemicals, size, geometry, volume or weight percentage, orientation, and spread of reinforcement which modify the properties of MMC. As a result, the developed composite have a greater specific strength, better fracture toughness, thermal expansion constant and used in high temperature environment. These are novel and current materials with great impact for the usage in aerospace applications such as missiles and shuttle vehicles, as well as high-temperature applications such as gas turbine components and automobile parts.

Ahamed et al [1] reported various fabrication methods used to prepare aluminium and zinc based composites. The casting and powder metallurgy routes were used as most popular techniques used by the industries to prepare aluminium type of matrix composites. When compared to powder metallurgy, the casting process produced quality sound castings due to the better mix of matrix and reinforcement and easy control of process parameters. Alam et al [2] analyzed the influence of graphite nanoparticles on mechanical behaviour of aluminum-based MMC. The hardness property of graphite-based MMC was increased by changing the weight percentage of nanoparticlecute beyond a specified limit. Ramnath et al [3] analyzed the mechanical behaviour of aluminum - born carbide particulate MMC prepared using stir casting process. The hardness, flexural strength, and internal features of the composite were analyzed and compared to aluminum. Prabhu et al [4] reported the metallurgical properties and mechanical behaviour of rutile re-inforced AA6061 aluminum alloy.
enhancement in strength was observed by addition of mass percentage of rutile particles. Kumar et al\textsuperscript{[5]} analyzed the tribological and strength properties of hybrid MMC. Influence of B\textsubscript{4}C and MoS\textsubscript{2} in matrix increased the wear resistance, decreased the wear rate and tensile strength of aluminium alloy. Kumar et al\textsuperscript{[6]} analyzed the influence of heat treatment on wear and mechanical behaviour of LM25 aluminium alloy based MMC. The mechanical characteristics were improved by adding alloying elements. Ravikumar et al\textsuperscript{[7]} characterized aluminum TiC composite and observed that the density of composite decreased with addition of TiC particles. Moreover, the strength and flexibility of the composite increased to a specific limit and decreased further addition of reinforcement. Soltani et al\textsuperscript{[8]} manufactured aluminum-silicon carbide particulate MMC using stir casting process. Interaction between reinforcement and matrix, ceramic particle proportion, and agglomeration of reinforcements phases were investigated using SEM. Hamid et al\textsuperscript{[9]} analyzed the effect of porosities and particle size on sliding type wear behaviour on aluminum - aluminum oxide based composites. The friction coefficient was increased in MMC as the porosity increased. Milan et al\textsuperscript{[10]} analyzed the particle size, volume, and matrix strength of Al-SiCp based MMC. It was observed that particle size on tensile strength depends on the type of matrix and matrix strength.

Bohi et al\textsuperscript{[11]} studied the combinational influence of Y\textsubscript{2}O\textsubscript{3} nanoparticle with ZnO rod on mechanical and microstructure of aluminum metal matrix composite. The strength was higher in hybrid composites due to the uniform spread of both rod and nanoparticle in matrix. Although, Bohi et al\textsuperscript{[12]} analyzed Zn nanorod on mechanical behaviour and microstructure characterization of aluminum type metal matrix composites. The maximum hardness was observed at 5\% of the ZnO nanoparticle.

Elwahed et al\textsuperscript{[13]} investigated the mechanical behaviour and thermal characteristics of Cu-ZrO\textsubscript{2} blended with graphene nanoparticles produced by the powder metallurgy route. The hybridizing sample with 0.5\% graphene nanoplatelets showed uniform distribution in Cu. The peak conductivity coefficient of 345 W m\textsuperscript{−1} K\textsuperscript{−1} was observed for 0.5\% graphene nanoplatelets. Sandown et al\textsuperscript{[14]} studied Al-Al\textsubscript{2}O\textsubscript{3} nanocomposite hybridized by graphene sheet. The maximum hardness of 130.52HV was observed at 1\% of graphene added in matrix. The electroless deposition was the primary factor for the improvement in strength. Mohamed et al\textsuperscript{[15]} correlated the relationship between grain boundary and ultra-fine-grained materials. The accumulated roll bonding process increased the young’s modulus. The enhancement in young’s modulus in roll bonded materials was due to the expanded atomic spacing in materials and grain boundary’s random atomic structure. Elwahed et al\textsuperscript{[16]} studied the wear and microstructural characteristics of ZrO\textsubscript{2}-Ti metal matrix composites. The maximum hardness of 570 HV was observed for 10 wt\% ZrO\textsubscript{2} particulate composites. It was noticed that wear rate was high with increment in sliding load and co-efficient friction lowered with increment in load. Wazery et al\textsuperscript{[17]} analyzed the electrical and mechanical properties of Zr-Ni functionally graded material fabricated through powder metallurgy technique. The linear shrinkage of non-graded materials showed low Ni content and the fracture toughness was improved by adding Ni wt of 0 to 50.

Sadoun et al\textsuperscript{[18]} reported improvement in strength and elasticity of friction stir tailor welded blank in AA2024 using interface layer AA7075 aluminum alloy. The effect of interface layer on mechanical and microstructural characterization were investigated and it was noticed that improvement in strength was due to the formation of strengthening precipitate Al\textsubscript{2}Cu and Mg\textsubscript{5}Zn. Moseley et al\textsuperscript{[19]} fabricated Al-SiCp metal matrix using roll bonding route. The authors developed a governing equation to predict the mechnanical properties and the model was validate using experimental results. Mohamed et al\textsuperscript{[20]} studied the influence of number bonding passes on tensile strength and microstructural characteristics of Al matrix reinforced SiC particle composites. The authors observed that introducing Al\textsubscript{2}O\textsubscript{3}-coated Ag particles enhanced the density of composites. The composite had higher Al\textsubscript{2}O\textsubscript{3} content of 15 wt\% offered higher wear resistance. Sadoun et al\textsuperscript{[21]} investigated the influence of Al\textsubscript{2}O\textsubscript{3} coated particles and Ag reinforcement on corrosive characteristics of Cu matrix nano type composites. It was observed that the resistivity of electrical conductivity was increased with further increasing Al\textsubscript{2}O\textsubscript{3} coated Ag. On the other hand, thermal conductivity was lowered by fusing the Al\textsubscript{2}O\textsubscript{3} coated Ag metal matrix composite. Fathy et al\textsuperscript{[22]} analyzed the impact of nano alumina and nano-silica on fatigue behavior of glass fiber - epoxy matrix polymer composites. It was noticed that addition of nano-silica from 0.5\%, the strength was decreased.

Several researchers attempted to develop single particle reinforced composites by reinforcing particles such as Al\textsubscript{2}O\textsubscript{3}, B\textsubscript{4}C, SiC and TiC. No attempt has been made to develop an LM13 aluminium alloy type particulate hybrid composite by addition of titanium diboride and boron carbide. Hence in this research work, an attempt is made to develop LM13 Al alloy-based hybrid composites by reinforcing titanium diboride and boron carbide by stir casting process. LM13 Al alloy is widely used as automotive pistons and other structural parts because of its high amount of silica content. The reinforcements were chosen based on mechanical behaviour such as hardness, yield strength, ultimate tensile strength and ability to withstand high temperature. Hence in this research work, LM13 Al alloy is taken as base material. Two reinforcements such as titanium diboride and boron carbide were used to prepare a hybrid composites. Stir casting technique is employed to prepare the composites.
The microstructures of castings are investigated using computer aided image analyzer. Density, porosity, Vicker hardness, yield strength, ultimate tensile strength and impact strength of composites are investigated.

2. Materials and methods

This research work produces LM13 Al type hybrid metal matrix composites using LM13 and two reinforcement particles such as TiB₂ and B₄C through stir casting method. The major and minor chemical elements of LM13 alloy is tabulated in table 1 shows the major element of Si upto 7%. The mechanical characteristics of LM13 aluminium alloy and reinforcements are presented in tables 2 and 3 respectively. LM13 aluminium alloy is supplied to the resistance furnace in the form of small blocks and its heated up to 850°C. When the molten melt reached a suitable temperature level, the premeasured quantity of reinforcement particles (TiB₂ and B₄C) are added to the melt slowly using a funnel. The wt% of titanium diboride is varied as 0,3,6,9,12,15 and a constant 3 wt% of boron carbide particles are used to prepare hybrid composites. The stirrer was rotated at 750 rpm while adding TiB₂ and B₄C into the molten LM13 aluminium alloy. The ceramic particulates are stirred thoroughly in the liquid metal. Further, the composite molten metal is poured in a cylindrical die of 25mm in diameter with 250mm height. The schematic representation of stir casting route is presented in figure 1(a). The stir cast route as shown in figure 1(b) is employed to produce aluminium matrix composites.

The required size of samples are cut from each combination and polished with different grades of sandpaper. Finally, alumina powder is used to make mirror-like polishing for further examination of microstructure of castings. The computer aided image analyzer is used to reveal the microstructure of the castings. Hardness, porosity, Vicker hardness, yield strength, ultimate tensile strength and impact strength of composites are investigated.

3. Results and discussions

3.1. Microstructure analysis

Aluminium LM13 alloy—TiB₂—B₄C reinforced composites are investigated using computer aided image analysis system. Aluminum dendritic structure is found to be uniformly dispersed in the microstructure of
aluminium LM13 casted alloy which are shown in figure 2. The supercooling of the casting during solidification phase transition produced this structure. In all the castings, the distribution of TiB$_2$ and B$_4$C indicates uniform dispersion in LM13 matrix (figure 3). This is due to the high stirring speed used to produce the quality castings. The reinforcement particles are thoroughly mixed with liquid molten metal during the stirring process which results in uniform distribution of particles throughout the castings.

Figure 1. Photograph of (a) schematic representation of stir casting setup, (b) Stir casting machine, (c) Tensile samples (before testing), (d) Tensile samples (after testing).
Table 4. Mechanical properties of LM13 - B₄C - TiB₂ composites.

| Trial No | Wt% of boron carbide | Wt% of titanium diboride | Cumulative wt% of reinforcements | Density (gm cm⁻³) | Porosity (%) | Hardness (VHN) | Impact Strength (J) | Elongation (%) | Yield strength (MPa) | UTS (MPa) |
|----------|----------------------|--------------------------|----------------------------------|------------------|--------------|---------------|---------------------|-----------------|----------------------|----------|
| 1        | 3                    | 0                        | 0                                | 2.671 ± 0.34%    | 1.2 ± 0.43%  | 70.4 ± 1.13%  | 2 ± 0.864%  | 6 ± 0.864%  | 99 ± 2.87%  | 151 ± 2.25% |
| 2        | 3                    | 3                        | 6                                | 2.686 ± 0.11%    | 1.21 ± 0.54% | 78.8 ± 1.13% | 3 ± 0.864%  | 5 ± 0.864%  | 102 ± 7.84% | 164 ± 1.38% |
| 3        | 3                    | 6                        | 9                                | 2.689 ± 0.11%    | 1.24 ± 0.54% | 82.2 ± 1.13% | 5 ± 0.864%  | 4.8 ± 0.864% | 118 ± 3.84% | 171 ± 2.65% |
| 4        | 3                    | 9                        | 12                               | 2.691 ± 0.07%    | 1.27 ± 0.83% | 88.4 ± 1.13% | 6 ± 0.864%  | 4.5 ± 0.864% | 122 ± 3.84% | 185 ± 2.65% |
| 5        | 3                    | 12                       | 15                               | 2.694 ± 0.04%    | 1.28 ± 0.83% | 91.5 ± 1.13% | 8 ± 0.864%  | 3.8 ± 0.864% | 128 ± 3.84% | 192 ± 3.24% |
| 6        | 3                    | 15                       | 18                               | 2.698 ± 0.04%    | 1.31 ± 0.83% | 96.2 ± 1.13% | 7 ± 0.864%  | 3.1 ± 0.864% | 124 ± 3.84% | 186 ± 3.24% |

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Figures 4 and 3 depict the variance of density and porosity of Al LM13 based particulate composites respectively. It is observed that as wt% of TiB$_2$ increases from 0–15 wt%, the density of composites increased from 2.671 gm/c.c. to 2.698 gm/c.c. It is due to the addition of higher density of TiB$_2$ reinforcement (4.52 gm/c.c.) in matrix. In addition, the porosity of samples increased with increment in wt% of reinforcements from 0–15 wt%. It is noticed that percentage of porosity increases from 1.2 to 1.31 by adding 15 wt% of TiB$_2$ with 3
wt% of B₄C in LM13 aluminium alloy. By increasing the surface of the surrounding gas layer around the reinforcements, it can boost locations for heterogeneous pore nucleation and increased porosity levels. Many researchers have found that enhancement of weight % of reinforcements improved the porosity and specific weight of MMC [23–28].

3.2. Hardness
Hardness is the property of the material which resist against indendation by a point load. The hardness of Al LM13 alloy—B₄C and Al LM13 alloy—TiB₂—B₄C reinforced dual particulate composites are investigated using vicker hardness tester. Table 3 present the average vicker hardness of samples tested at three separate regions. The hardness properties of hybrid MMC combinations are shown in figure 5. It is noticed that hardness of LM13 alloy increased with addition of wt% of TiB₂ and B₄C paricles in Al LM13 alloy. A peak micro hardness of 96.2 VHN is noticed for the matrix had 15 wt% of titanium diboride particles with 3 wt% of boron caride reinforcements. It is about 36.6% enhancement in hardness when compared to Al LM13 alloy reinforced with 3 wt% of B₄C particles. The homogeneous distribution and size of ceramic particles, as well as the wt% of reinforcement, improved the bulk and micro hardness of MMC. In addition, grain reinfinement during the solidification process which improves the hardness properties of samples. Several researchers examined that hard ceramic particles enhanced the strength of base Al matrix [29, 30].
3.3. Tensile strength

Figure 6 shows the tensile strength of Al based MMC with various wt% of reinforcements. It can be seen that wt% of yield strength and ultimate tensile strength of Al LM13 matrix increased with addition of wt% of reinforcement from 0–12 wt% of titanium diboride particles in Al LM13 alloy. This is because of the addition of brittle ceramic particles which enhanced the strength of base alloy. This is because of dispersion strengthening mechanism that reinforcement phases which acted as load carrying elements when it's subjected to tension. It prevents the crack initiation, propagation which offered high bearing load capacity which increased the tensile strength of material. Moreover, the dislocation of grains during tensile load is restricted by the fine and evenly distributed reinforcement particle in the grain boundary gives anchoring effect. This phenomenon may be one of the factors for the strength improvement. In general, there are two mechanisms involved in strength enhancement such as direct and indirect mechanism: the first one is based on the load transferring from matrix to harder ceramic particle at the interface and the later one is due the thermal expansion co-efficient of reinforcement particles and matrix. Maximum tensile strength of 192 MPa is noticed for Al LM13 alloy contains 12 wt% of TiB₂ and 3 wt% of B₄C particles. It shows an improvement upto 27.15% when comparing to Al LM13 alloy contains 3 wt% of boron carbide particles. When the TiB₂ reinforcement increases beyond 12 wt%, it decreases the tensile strength and yield strength of LM13 aluminium alloy (figure 7). This may be the presence of air gap between the LM13 alloy and reinforcement phases which behaves as crack initiation regions which results failure of composites. It can be verified with level of porosity that high wt% reinforcement composites had higher porosity. The large discrepancy in thermal expansion co-efficient between reinforcements and aluminum.
matrix might cause dislocation volume increases and other flaws in ceramic particle areas. Based on Orowan strengthening mechanism [31–34], few parameters like significant refinement of grains and the ceramic phases in matrix, production of dislocation which resulted lower strength of material. However ultimate tensile and yield strength of 15 wt% TiB2—LM13 composite offered better properties as compared to 9 wt% TiB2—LM13 aluminium alloy composites.

3.4. Impact Strength:
The variation of impact strength of titanium diboride—boron carbide reinforced hybrid aluminium based particulate MMC is presented in figure 8. It is noticed that wt% of TiB2 reinforcements increased the impact strength when comparing to Al LM13 alloy reinforced B4C composites. As the wt% of TiB2 increased from 0–12, energy absorbed by the material is increased from 2–8 J. It is due to the addition of TiB2 reinforcement phase which improves energy absorption capacity of matrix. This can be verified using Vicker hardness of materials that composite with higher wt% offered higher strength to the matrix. When the impact load acting on matrix, the hard reinforcement particles absorbed the load and offered high impact strength to the material. A peak impact strength of 8J is observed the LM13 aluminium alloy contains 12 wt% of TiB2 and 3 wt% of B4C. It shows an increment up to 300% when compared to LM13 aluminium alloy—3 wt% B4C composites. However the addition of TiB2 beyond 12 wt% decreased the impact strength of composites. This may be due to the higher level of porosity which results in failure at early stages [35, 36]. The strength dropped may be the formation of higher porosity and few cluster of TiB2 particles in Al LM13 alloy. However impact strength of composite contains 15 wt% of TiB2 offered high impact strength when compared to the composite had 9 wt% of TiB2 particles.

4. Conclusions
Aluminium LM13 alloy reinforced TiB2 and B4C dual particle reinforced hybrid MMC is fabricated through stir casting technique. Weight percentage of TiB2 is varied from 0–15 wt% and a constant 3 wt% of B4C is added in the matrix. The microstructure of the castings are examined and mechanical properties viz., hardness, yield strength, ultimate tensile strength and impact strength are examined. The major conclusions are presented as below:

1. Microstructural characteristics of castings shown that uniform distribution of reinforcement particles in aluminium LM13 alloy. This is due to the high stirring speed used in stir casting route which resulted uniform spread of titanium diboride and boron carbide ceramic reinforcements in aluminium LM13 alloy.
2. Micro hardness of aluminium is enhanced with varying TiB2 content from 0–15 wt%. A peak hardness of 96.2 VHN is noticed for the matrix had 15 wt% of titanium diboride particles with 3 wt% of boron carbide particles. 36.6% improvement in hardness is observed when comparing to Al LM13 alloy reinforced with 3 wt% of B4C particles.

Figure 8. Variation of impact strength with cumulative wt% of reinforcements in Al LM13 alloy.
3. Ultimate tensile strength of aluminium LM13 alloy is improved by the adding TiB₂ wt% from 0–12. Maximum ultimate tensile strength of 192 MPa is noticed for Al LM13 alloy contains 12 wt% of TiB₂–3 wt% of B₄C particles. It shows an improvement upto 27.15% when comparing to Al LM13 alloy contains 3 wt% of B₄C particles. However further addition of TiB₂ wt% decreases the ultimate tensile behaviour of LM13 Al Alloy.

4. Adding TiB₂ in matrix improves the impact behaviour of LM13 Al alloy. Increasing TiB₂ wt% from 0–12 increased the impact strength of Al alloy from 2–8 J. On the other hand, further addition of TiB₂ decreased the impact strength of material. This may be due to the higher level of porosity and thermal mismatch coefficient between the ceramic/aluminium alloy, which might lead to local stress production.

The developed Al LM13 alloy—titanium diboride—boron carbide reinforced MMC can be used as structural parts in automobiles, aerospace, marine and defense fields because of its superior mechanical behaviour as comparing to single particle reinforced composites.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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