Silicon (2022) 14:4197–4206
https://doi.org/10.1007/s12633-021-01210-4

ORIGINAL PAPER

Effect of 6 Wt.% Particle (B_4C + SiC) Reinforcement on Mechanical Properties of AA6061 Aluminum Hybrid MMC

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Received: 10 March 2021 / Accepted: 14 June 2021 / Published online: 20 June 2021

Abstract
Aluminum based hybrid metal matrix composite with more than two particle reinforcement is very much popular for heavy duty application, and the proportion of these particle reinforcement can be controlled to achieve desired mechanical properties (strength and wear resistance). AA 6061 alloys popularly used in aircraft and automobile applications, tends to have inferior tribological property and therefore particle reinforcements are being made to strengthen the matrix. The prime objective of this investigation is to study the effect of varying wt.% of proportionate individual reinforcement (SiC and B_4C) on the mechanical properties of a particular composition (6 wt.%) of AA 6061 hybrid composite. The present investigation is done to evaluate the dependance of hard particle reinforcements on the strength and elongation behaviour of hybrid composite. Hardness measurement and uniaxial loading techniques were used to characterize the mechanical properties of the as-cast hybrid composites, whereas OM, XRD and SEM analysis was done to study the distribution of reinforcement within the base (AA 6061) metal matrix phase. The improvement in mechanical properties, such as Vickers hardness, UTS, yield strength and elongation were presented and explained using various hypothesis proposed by previous studies. The role of *clustering theory* and *effect of binary eutectic Mg_2Si phase* found to be key the enhanced mechanical properties of the hybrid composites. Addition of *Alkaline Earth Metal* (Mg) during the synthesis process have led to an increase in the elongation of hybrid composite with the increase in wt.% of reinforcement which is analogous to the effect of alkali metals ('Na' and 'Li') addition that helps in refining the Mg_2Si Eutectic phase.

Keywords Hybrid composites · Clustering theory · Mg_2Si eutectic phase · 6 wt.% (SiC+B_4C) · Elongation · UTS

1 Introduction

Al based Metal Matrix Composites (MMCs) are extensively used in automotive applications due its light weight and excellent mechanical properties. Despite having such outstanding property, continuous efforts are being made to improve its strength and stiffness, and as a result of this, researchers have tried to add numerous reinforcement (particle) into the base metal [1]. As far as reinforcements are concerned, variety of filler materials ranging from macro to nano size particles in both polymer and metal matrix composite, fiber type filling materials for laminated composites and some cryo-treated particle hardened filler material are commonly practiced for the synthesis of composite material [1–4]. Out of these reinforcements discussed, Aluminum [MMCs] with particulate reinforcement showed promising results in the form of improved strength and high stiffness which are more desirable for automotive and aircraft industry.

While discussing about the particulate reinforcement, researchers from all over the world have worked with ceramic based hard particles (SiC, Al_2O_3, MgO, WC, and B_4C) for Al based composite to strengthen the base material [5]. With the development in production technology, a new trend was adopted while preparing composites using two or more reinforcement to impart high specific strength, high toughness and better ductility property compared to conventional techniques [6–8]. As far as the use of SiC as a reinforcement to the base material (AA 6061) is concerned, it substantially increased

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both the mechanical and tribological properties of the composite due to its high hardness [9–11]. In addition to the conventional liquid metallurgy route, researchers have also tried powder metallurgy route to produce in-situ hybrid composite of AA6061, SiC and graphite particles [12]. A group of researchers have shown remarkable improvement in the tribological property of AA6061/SiC hybrid composite by adding a fixed proportion of boron carbide (B_4C) to the Aluminum metal matrix [13]. There are instances, where researchers have reported an increase in hardness and wear property of hybrid composite with the increase in SiC particle content [14, 15]. The role of boron carbide (B_4C) is found to be identical to silicon carbide (SiC) particle which has also improved the tribological property significantly [16]. The improvement in tribological property due to boron carbide addition (B_4C) is due to its intersection bonding with Al matrix in comparison with SiC and Al_2O_3 particle [17]. Silicon carbide-based hybrid composites are also studied with other Al alloys such as A356 and they also show promising results [18, 19]. A comparison of individual properties of AA6061 aluminum alloy, B_4C and SiC is given in Table 1, and the density of Al base alloy is almost equal to the boron carbide, whereas the SiC seems to be relatively dense. The hardness of boron carbide and Silicon carbide is much higher than Al base alloy and the presence of B_4C (hardest among all) may affect the hardness of the Al hybrid metal matrix composite [AHMMCs].

There has be many compositions of AA 6061 based hybrid composite with varying proportion of SiC/Al_2O_3/B_4C/Gr tried by many researchers to obtain enhanced properties; however, very little efforts were made to study some compositions those maintain a fixed proportion of the total reinforcement with the base metal [41–44]. In this investigation, efforts were made to study certain unique set of compositions (AA6061/SiC/B_4C), where the weight fraction of both SiC and B_4C are maintained in such a pattern such that the maximum reinforcement are restricted to 6 wt.% only. The effect of increasing B_4C addition were studied with the decreasing SiC addition by maintaining a fix reinforcement with the base metal. The as-cast hybrid composites were characterized and their strength, hardness and elongation was compared with the base AA6061 alloy.

Table 1 Physical properties of AA6061/B_4C/SiC [20, 21]

Properties	AA 6061	B_4C	SiC
Density (g.cm $^{-3}$)	2.7	2.52	3.21
Elastic Modulus (GPa)	60	470	410
Poisson's Ratio	0.33	0.21	0.14
Hardness (HB 500)	30	380	280
Tensile Strength (MPa)	115 (T)	550(T)	3900 (C)

2 Materials and Method

In this present investigation, Al 6061 rectangular blocks were cut out of the as-cast ingots for the preparation of Hybrid Aluminum Composite using stir casting technique. The composition of the as-rec Al alloy was confirmed from the Optical Emission Spectroscopy (OES) and the elemental composition of the alloy is given in Table 2. The Emission Spectroscopy technique used for the elemental composition analysis of bulk sample is very much reliable due to its complexity and economic aspects, compared to other conventional spectroscopy technique [22]. The synthetic ceramic particles (SiC and B_4C) of size 15–60 μm, used for the preparation of hybrid composite are procured from *Alfa Easer*.

3 Preparation of AA6061 Hybrid Composite

The four samples (S1, S2, S3 and S4) including as-cast AA6061 base alloy with varying composition of SiC (2 wt.%, 3 wt.%, 4 wt.%) and B_4C (4 wt.%, 3 wt.%, 2 wt.%) were prepared using liquid metallurgy technique (stir casting) (Table 3). The compositions were chosen based on a study conducted by a group (*Halili et. al., 2019*) where the total reinforcement was fixed (12 vol.%) by adjusting the individual particle reinforcement rationally [45]. The stir casting method is considered as the most economical method where, it can be ensured that the homogeneous mixing of reinforcement in the metal matrix [23, 24]. The entire experimental setup for the synthesis were shown in Fig. 1. The stir casting parameters were chosen based on standard processing parameter practiced in literature (*Bhandare et. al., 2013*) and by conducting few trials to obtain composites with less porosity [46]. Prior to the casting, the rectangular aluminum blocks were cut into further pieces to get accommodated into the graphite crucible and melted in an electric arc furnace at temperature of 750 °C to ensure complete liquification of Aluminum. The ceramic particle reinforcement (SiC and B_4C) was pre-heated in an oven (at 250 °C) to remove moisture content present in the particle. The pre-heated SiC and B_4C particles were added to the molten metal after the complete liquification of AA6061 alloy present in the graphite crucible and stirring was done in the range of 400–500 rpm for 4–6 min. to produce a homogeneous mixture of composite material [25, 26]. To improve the wettability of the ceramic particle reinforcement and better miscibility with the molten metal a thickening agent (0.5 wt.% of Mg) was added at the slurry stage. Few degassing tablets (C_2C_{16}: solid hexa-chloroethane) weighing ~3 g. was added to the vortex of whirling molten pool during stirring to reduce porosity in the hybrid composite. After the completion of stirring, hot molten metal mixture (~ 700 °C) was poured into the pre-heated metal mould cavity (150 mm × 15 mm × 15 mm) at a temperature

Table 2 Chemical composition of AA 6061

Element (AA 6061)	Mg	Si	Fe	Cu	Ti	Cr	Zn	Mn	Al
Weight %	0.95	0.75	0.7	0.3	0.15	0.25	0.25	0.15	Balance

400 °C followed by a uniform cooling in the ambient temperature.

4 Results and Discussions

4.1 Material Characterization

4.1.1 Optical Microscopy

The cast samples of different composition were cut into small pieces (15 mm × 20 mm × 10 mm) and cold mounted for microstructural analysis. The mounted samples were polished till mirror surface finish achieved using emery sheets (400, 600, 800 and 1000) followed by Alumina polishing. The polished samples were etched with Keller's reagent and micrographs were taken using LECO Olympus BX53M Microscope [27]. The micrographs of all the samples with varying composition were studied for phase analysis and particle distribution. In the as-cast base AA6061 alloy (S1), few Mg_2Si phases (shown in Fig.2a) were detected in the matrix, whereas for the samples (S2, S3 and S4) tend to have uniform distribution (shown in Fig. 2b,c and d) throughout the matrix. The microstructure analysis reveals that there is no agglomeration of SiC and B_4C particle, and the reinforcements were evenly distributed throughout the hybrid composite matrix.

4.1.2 SEM and XRD Study of Hybrid Composite

Prior to elctron microscopy (SEM) and X-Ray diffraction analysis, the samples were polished with mirror finsih surface using emry sheets. High magnification SE images of the polished hybrid composite samples were taken using Jeol J-6000 Plus Scanning Electron Microscope (SEM) to study the ceramic particle (SiC and B_4C) reinforcement. The formation of Mg_2Si Eutectic phase can be confirmed form both optical and SEM imges shown in Figs. 3a and 4a, respectively. To support this claim, additional experiments such as XRD analysis was odne on the polished samples using Pananalytical X'Pert system (2 $= 20^0–120^0$; Scan rate = 2^0 per min). The phases appearing in the hybrid composite are shown (Fig. 3c) in the XRD pattern marked with symbols ('+':Mg_2Si, '#':SiC, '*':B_4C). The most intense peak of Al base matrix phases are indexed as (1 1 1), (2 0 0), (2 2 0) and (3 1 1).

In addition to the particle reinforecment, some other features such as micro-pores were also seen in th matrix phase of all the SEM images shown in Fig. 4. It can be evident from these images that the B_4C particle are having irregular shape and the average diameter is near to 100 μm, and similar features was also observed for SiC particle whose size is relatively smaller than boron carbide particles. The size of boron carbide particles seems to be uniform in most of the composite, and no sign of clustering/aggolomoraion is discovered at micron level. There are enough proof on the formation of micron level pores ranging from 1 to 10 μm throughout the aluminum matrix.

Table 3 Percentage of reinforcements

Specimen	AA 6061 (wt.%)	B_4C(wt.%)	SiC(wt.%)
S1	100	0	0
S2	94	2	4
S3	94	3	3
S4	94	4	2

4.1.3 Indentation Test Results of AA6061 Hybrid Composites

The bulk hardness of the mounted samples (S1-S4) was experimentally calculated using Brinell Hardness Scale. The test results (shown in Fig. 5a) reveal that there is a proportional improvement of hardness with the increase in B_4C wt.% in the hybrid composites. Conventionally, the effect of boron carbide (B_4C wt.%) was found to be predominant in the increase in hardness of AA6061/B_4C and AA6082/B_4C composite (shown in Fig. 6b), whereas there is a dearth of literature that can justify the increase in hardness with the increase in SiC wt.% of AA6061 hybrid composite produced via liquid metallurgy route. However, a study on AA6061/SiC composite has justified the increase in hardness (HV) and Compressive Strength (shown in Fig. 6d) value with increase in SiC (wt.%) [28]. In the present investigation, the SiC wt.% for the samples (S2-S4) was replaced with the B_4C wt.% to maintain a fixed reinforcement and the addition of the hard B_4C particles have helped in compensating the effect of SiC that is responsible for increase in hardness of majority of hybrid composite (AA6061/SiC). Except one recent study (shown in Fig. 6b) by a group of researcher lead by *Hynes et. al., 2020* [29], almost all work showed an

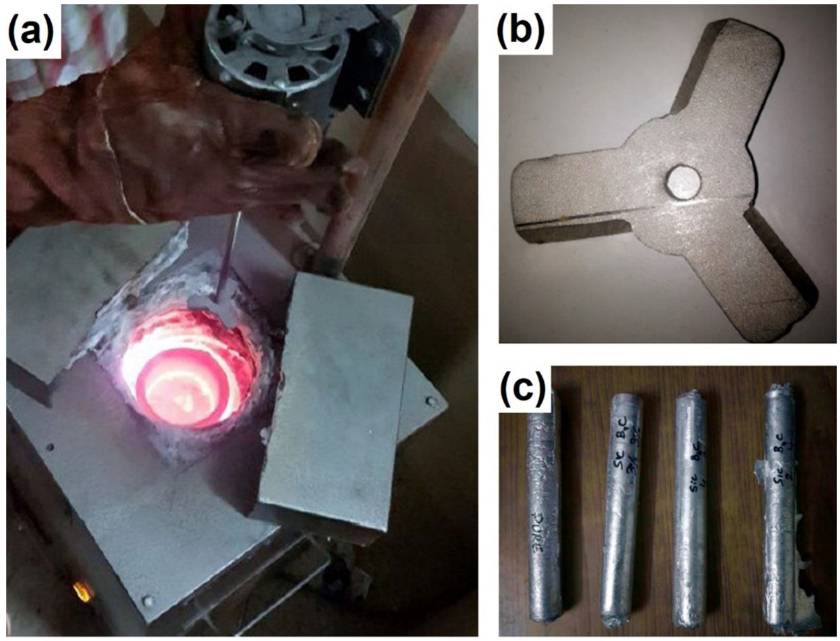

Fig. 1 **(a)** Stir casting setup used for synthesis of AA 6061/SiC/B_4C hybrid composite; **(b)** Blade geometry used for stirring process; **(c)** Images of cast composites

increase in hardness by the addition of B4C in Al matrix based hybrid composites [10, 30, 31]. The fluctuation in hardness value in the work presented by the group (*Hynes et. al., 2020*) might be due to the imropoer mixing of B_4C particles. The microstructre analysis of the composites in present investigation has ruled out any possibility of aggolomoration or improper mixing, and hence the results are very much reliable.

4.1.4 Uniaxial Tensile Test Results of AA6061 Hybrid Composites

The tensile tests were conducted on cylindrical as-cast AA6061 hybrid composite based on ASTM-E-8 M specifications using INSTRON 8801 Servo hydraullic tensile tester [32]. Prior to the uni-axial loading the gauge section was polished using fine grade emery sheet to eliminate any pre-

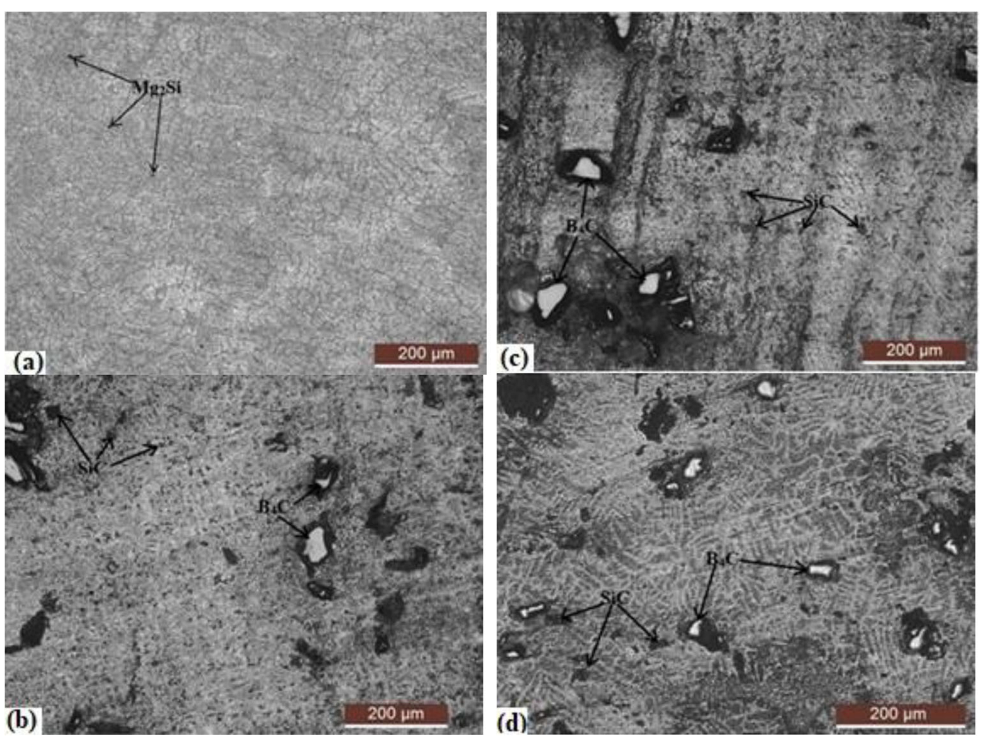

Fig. 2 **(a)** Pure AA 6061 microstructure Specimen S1; **(b)** 4 wt.% SiC and 2 wt.% B_4C hybrid composite microstructure specimen S2; **(c)** 3 wt.% SiC and 3 wt.% B_4C hybrid composite microstructure specimen S3; and **(d)** 2 wt.% SiC and 4 wt.% B_4C hybrid composite microstructure specimen

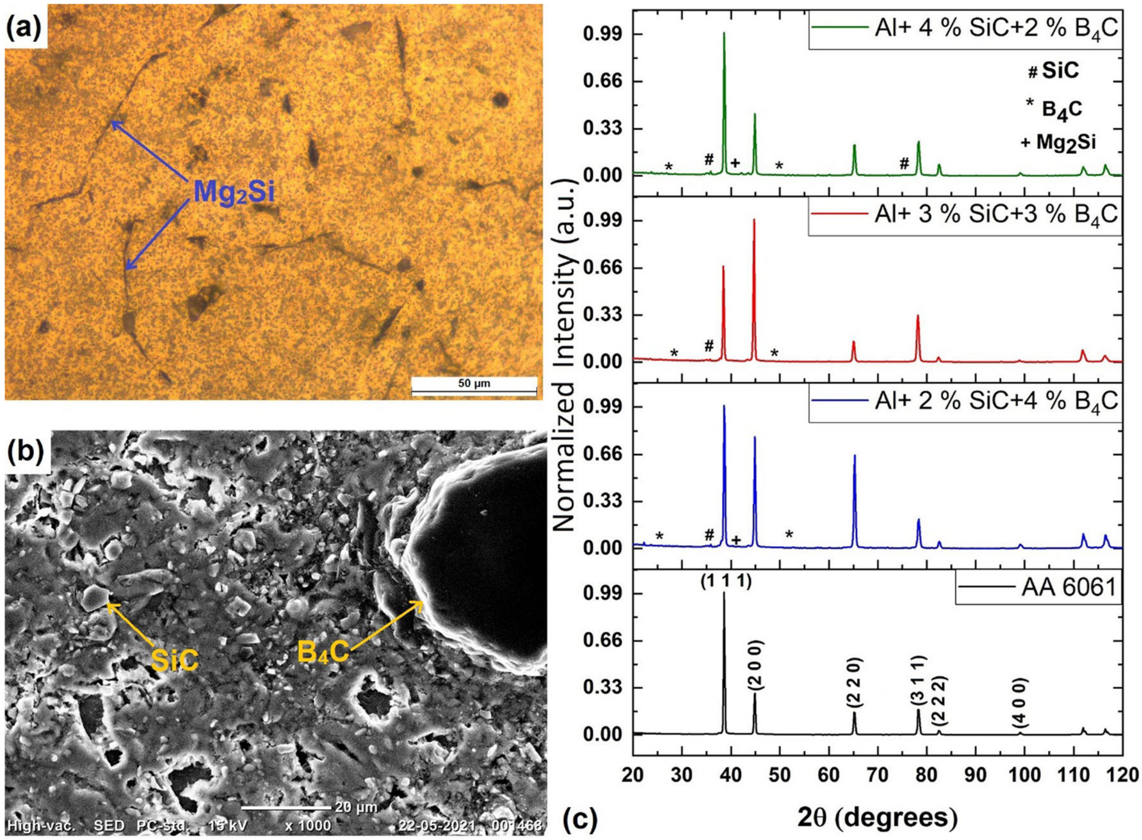

Fig. 3 (**a**) Optical micrograph of as-cast AA6061 alloy showing Mg_2Si Phase; (**b**) SEM image of AA 6061 + 4% SiC+2% B_4C hybrid composite showing SiC and B_4C particle reinforcement; (**c**) XRD plots of AA 6061 hybrid composite showing SiC and B4C reinforcement

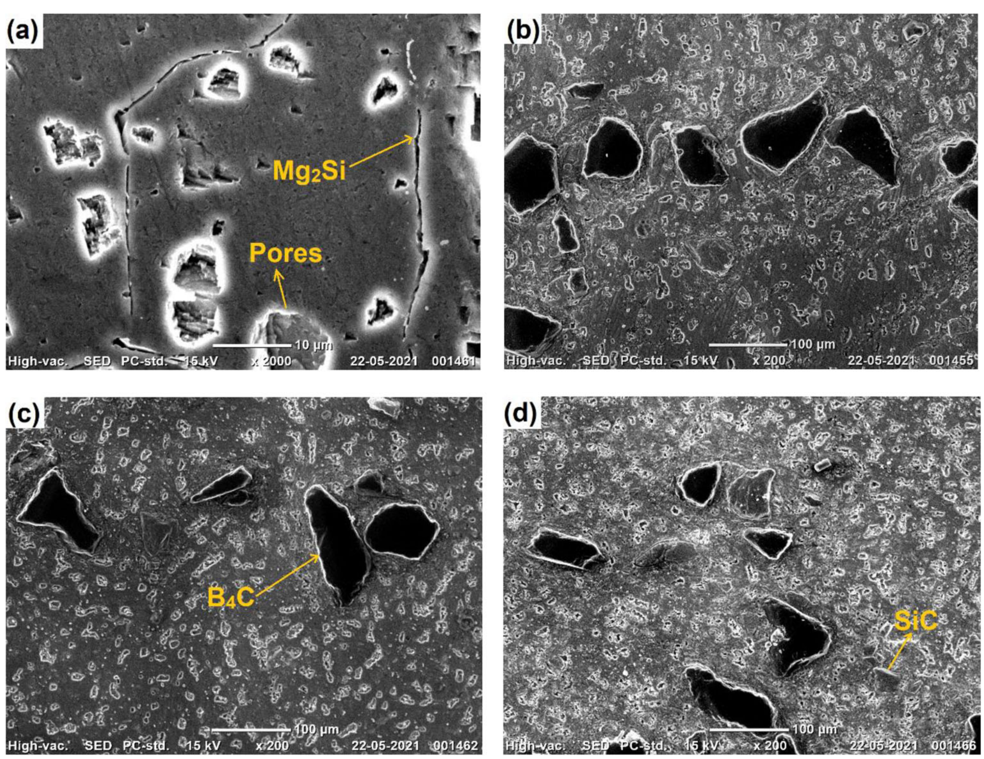

Fig. 4 (**a**) SEM image of as-received AA 6061 alloy; (**b**) SEM image of AA 6061 + 2% SiC+4% B_4C alloy; (**c**) SEM image of AA 6061 + 3% SiC+3% B_4C alloy; (**d**) SEM image of AA 6061 + 4% SiC+2% B_4C alloy

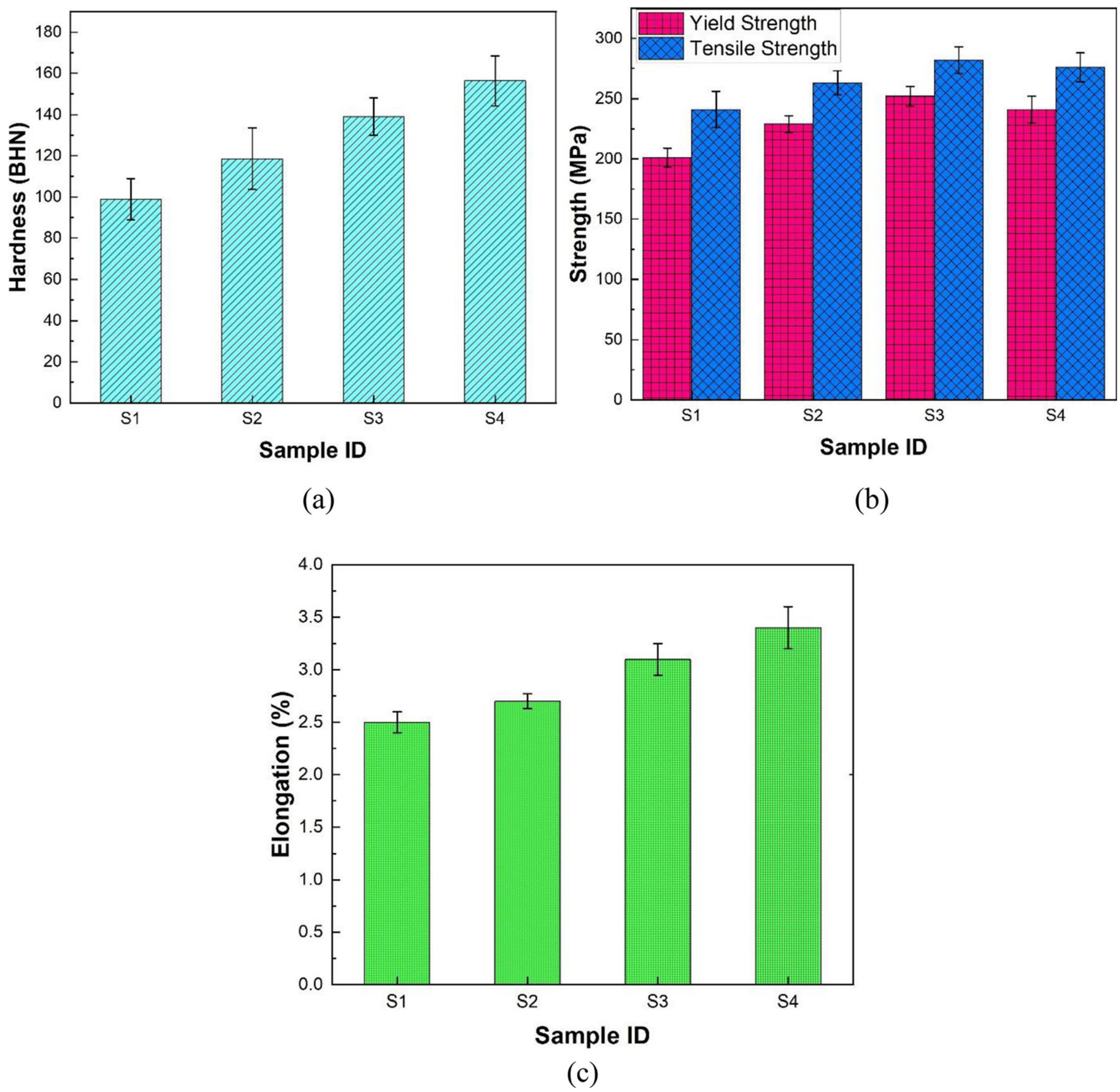

Fig. 5 (**a**) Brinell hardness; (**b**) Yield strength and Ultimate tensile strength; (**c**) Elongation of as-cast hybrid matrix with 6 wt.% reinforcement with varying proportion of B_4C and SiC

existing crack during machining [33]. The UTS and yield strength of all the samples (S1-S4) is shwon in Fig. 5b, and the strength of the composites (S2 and S3) with reinforcement has shown higher value compared to the base alloy. But the composition (S4) with 2 wt.% SiC and 4 wt.% B_4C has shown a reduction in both yield and tensile strength. However, the elongation (Fig. 5c) for the hybrid composites (S2-S4) shown continious improvement compared to the base alloy (AA6061).

The Ultimate Tensile Strength of AA6061/B_4C composites generally increases with the increase in both the B_4C wt.% (shown in Fig. 6a) [10, 21, 30, 31], 34] and B_4C vol.% (shown in Fig. 6c) [21, 35, 36]. But, in the case of *Hynes et. al., 2020* [29], the strength keeps on decreasing with the increase in B_4C wt.%. However, such exception in reduction in strength might be due to two reasons: (i) Improper mixing of reonforcement particle/ agollomoration of particles during mixing; (ii) the tensile sample preparation (some pre-existing cracks during machining of gauge section). The work carried out by *Sharma et. al.,2019* [21], showed that the strength increases with the B_4C addition and then decrease. The present set of results realted to strength is analogous with the results produced by *Sharma et. al.,2019*. It can be noted that the 6 wt.% reinforcement which contain both $B_4C$and SiC particle ranging from only 2–4 wt.% in the Al hybrid composite is able to achieve strength in the range of 250–270 MPa. Whereas, previous work done on either SiC or B_4C have achived the strength more than 220 MPa with B_4C particle above 7 wt.% [21, 34].

$$\sigma_y = \sigma_m V_m + \sigma_r V_r \quad (1)$$

$$\sigma_y^{modified} = \sigma_m V_m + \sigma_r V_r - 2\sigma_r V_c \quad (2)$$

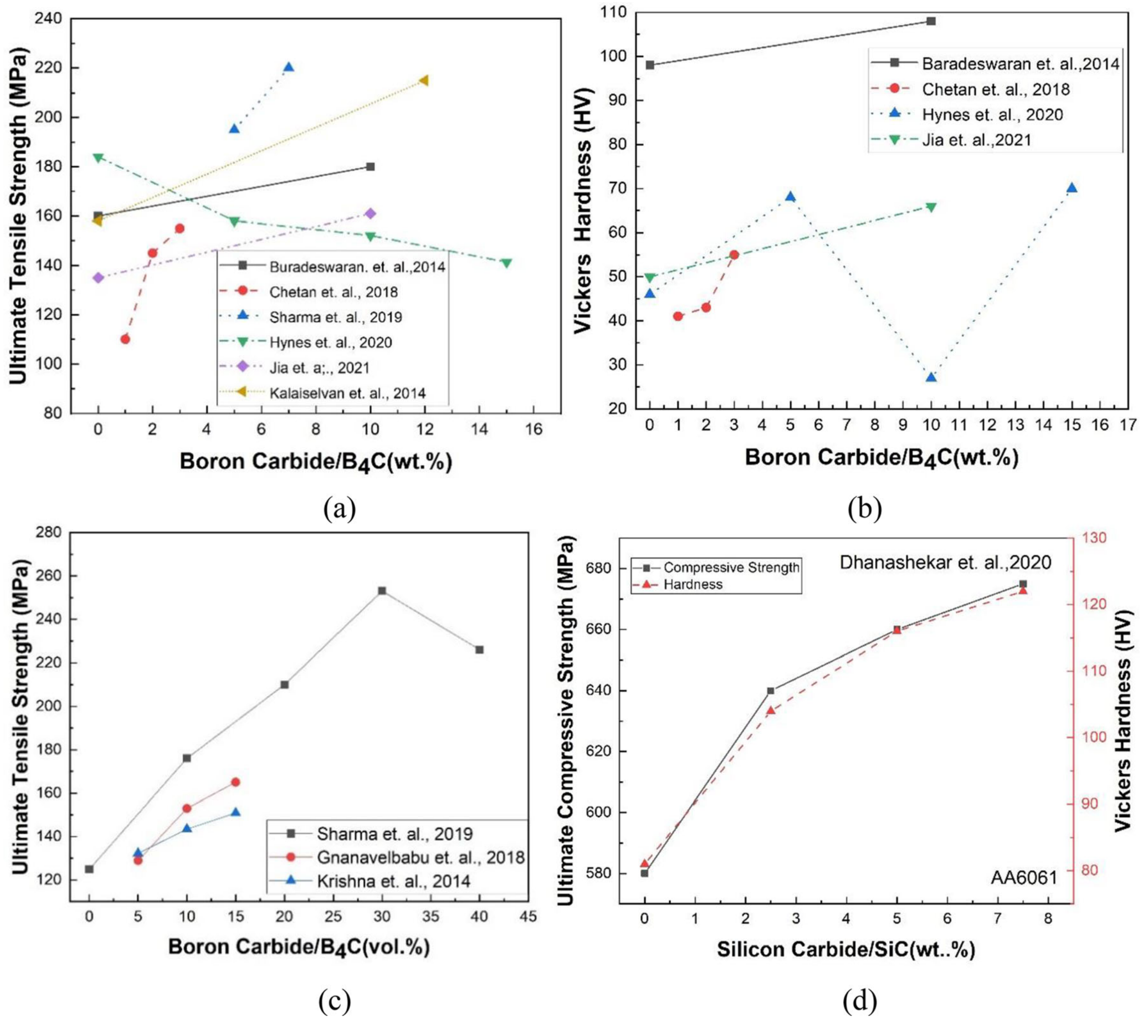

Fig. 6 (**a**) Effect of B_4C/boron carbide (wt.%) addition on Ultimate Tensile Strength; (**b**) Effect of B_4C/boron carbide (wt.%) addition on hardness; (**c**) Effect of B_4C/boron carbide (vol.%) addition on Ultimate Tensile Strength; (**d**) Compressive Strength and hardness of AA6061/SiC composite with increasing SiC wt.%

Where, σ_m= Strength of metal matrix (MPa)
σ_r = Strength of reinforcement (MPa)
V_m = Volume of matrix
V_r = Volume of reinforcement.
V_c = Volume of cluster.

The present investigation has created a scope for studying on achieving best mechanical properties with optimized particle reinforecement to the Al base metal, because it is difficult to avoid any deletirious effect of excessive particle reinforcement on the strength of hybrid composites. This can be proven through the "*Theory of Clustering*", where *Hong et. al., 2003* tried to explain by comparing the theoretically calculated strength (shown in Eq. 1) with experimentally investigated strength [37]. The experimental strength value drops after a saturated reinforcement is achieved, however the calculation shows an increasing trend. Therefore, the variation in strength is due to the formation of cluster and the modified theortical strength was given by Eq. 2.

4.2 Effect of Mg Addition on Elongation of AA6061/ B_4C/ SiC Hybrid Composite

When comparisons were done on the UTS and Elongation of AA 6061/B_4C/SiC for the present investigation with the study done by *Poovazhagan et. al.,2013* [38], very interesting facts were reveled. As far as compositions are concerned the net reinforcement of the hybrid composite samples (C1-C4) are not much differing from the compositions of (S1-S4) the composite with 6 wt.% (SiC+B_4C). The increase in SiC vol.% by keeping the B_4C vol.% by *Poovazhagan et. al.,2013* has shown a continious decrease (shown in Fig. 7a) in the elongation (%) of hybrid compsite samples (C1-C4),whereas in the present investigation, the increase in B_4C wt.% by proportionately decreasing the SiC wt.% has led to an increase (shown in Fig. 7b) in elongation (%) of the hybrid composites. It means, the B_4C addition has certainly some effect on the improvement in the elongation, but there is not enough evidence or

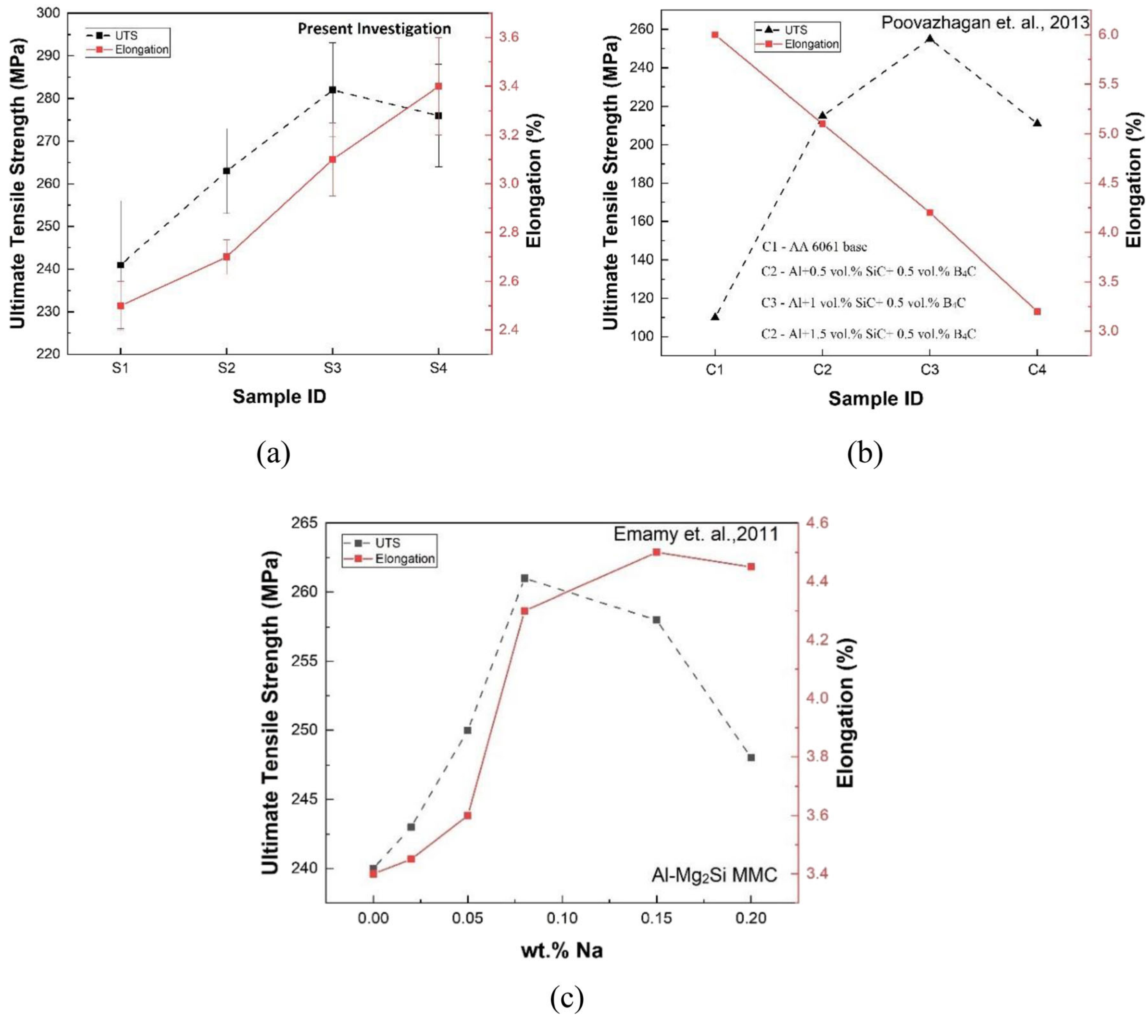

Fig. 7 Ultimate tensile strength and Elongation comparison between, (**a**) Present investigation; (**b**) *Poovazhagan et. al.,2013*; and (**c**) Effect of 'Na' on UTS and Elongation of Al-Mg_2Si MMCs

literature to proove this theory. However, there are literature availble that shows that addition of Alkali metals such as Li and Na has improved the elongation in Al based Metal Matrix Compsites.

A study conducted by *Emamy et. al., 2011* on the effect of 'Na' addition on the improvement of tensile property of Al-Mg_2Si Metal Matrix Composites [39]. The 'Na' addition has moved the *binary eutectic point* towards the Mg_2Si rich direction which changed the Mg_2Si phase distribution (more uniform) and size/morphology. This change has increased (shown in Fig. 7c) the UTS and elongation of the composite for certain range of 'Na' wt.% addition, however the reason for such increase is not yet understood. Similar study was conducted by *Hadian et. al.,2008* on the Al-15 wt.% Mg_2Si composite, where 'Li' addition has improved UTS and elongation of the as-cast composite [40]. The hypothesis was given that 'Li' might have shifted the eutectic point Mg_2Si rich side of the diagram by changing the surface energy of the Mg_2Si phase. For the present investigation 0.5 wt.% 'Mg' was added as a thickening agent during the synthesis of the hybrid composite and this has led to a uniform and fine distribution of Mg_2Si network troughout the matrix. These changes in the microstructre might have led to an increase in elongation of composites even with increased B_4C content. To prove this hypothesis more study need to be done on such compositions.

5 Conclusions

The mechanical properties of AA6061/SiC/B_4C hybrid composite using stir casting method were explicitly studied, and the significant outcomes of the investigation are presented as follows:

(i) The optical microscopy (OM) results reveal that the homogeneous distribution of dual particles (SiC and B_4C) within the AA6061 matrix. Besides OM results, other characterization techniques such as SEM and XRD analysis of hybrid composites were conducted on the hybrid composites to ascertain the presence and uniform distribution of dual particles within the matrix.
(ii) The presence of ceramic particles (SiC and B_4C) was confirmed from the XRD peaks along with major peaks (indexed) from the base AA6061 alloys. Some additional features (casting defect/ micro-pores) were discovered within the as-cast composite from the SEM study.
(iii) As far as mechanical properties are concerned, the hardness (BHN) value of hybrid composite (AA6061 + 4% B_4C+ 2% SiC) shows 60% improvement when compared with the AA6061 base alloy. Such enhancement in hardness is due to the presence of hard B_4C particles within the matrix.
(iv) However, a similar improvement in tensile strength (UTS) and yield strength (YS) did not reflect in the case of the composite with 4% B_4C and 2% SiC reinforcement. Rather, the composite with an equal fraction of reinforcement (3% B_4C and 3% SiC) showed the highest UTS and YS value compared to other compositions and base alloy. The reduction in UTS and YS for the composite with 4% B_4C might be because of clustering effect (strength decreases after reaching an optimum reinforcement level within the matrix).
(v) While discussing the elongation results of the as-cast hybrid composites, the composition with 2% SiC and 4% B_4C showed the highest elongation compared to other compositions, including the base alloy. This is supposed to be a contradicting result; however, such improvement in elongation might be due to the addition of alkaline earth metal (0.5 wt.% Mg). The Mg addition has led to the refinement of Mg_2Si phase throughout the matrix, which helped in improving the elongation of the hybrid composite.

Acknowledgements The authors are thankful to RINL, VIZAG Steel Plant for carrying out Optical Microscopy study and hardness measurement.

Author's Contribution Divakar Bommana - Conceptualization, Data curation; T Rajesh Kumar Dora - Formal analysis, Writing - original draft; N Pallavi Senapati-Resources; A Sunny Kumar- Resources.

Funding The entire work is funded by the authors and no separate funding is received.

Availability of Data and Material The data collected from the experiments are true to their value. No fraudulent practices are used to generate the data.

Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of Interest There is no conflict of interest among the authors.

Compliance with Ethical Standards This section is not applicable for the present research because no animal or human are involved.

Consent to Participate The consent form is attached separately in the submission file.

Consent for Publication The consent to publish gives the publisher the permission of the author to publish the work.

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