Effect of 6 wt.% Particle (B4C+SiC) Reinforcement on Mechanical Properties of AA6061 Aluminum Hybrid MMC

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Research Article

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Posted Date: April 12th, 2021

DOI: https://doi.org/10.21203/rs.3.rs-313934/v1

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

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Abstract

Aluminum based hybrid metal matrix composite with more than two particle reinforcement is very much popular for heavy duty application. In the present study, mechanical properties of AA6061 based hybrid composite synthesized using liquid metallurgy route with 6 wt. % total reinforcement (B_4C+SiC) with different proportions of B_4C wt. % and SiC wt. % were investigated. Hardness measurement and uniaxial loading techniques were used to characterize the mechanical properties of the as-cast hybrid composites. The improvement in mechanical properties, such as Vickers hardness value, UTS, yield strength and elongation were tried to explain using various hypothesis proposed by previous studies. The role of *clustering theory* and *effect of binary eutectic Mg_2Si phase* have played a key role in defining the mechanical properties of the hybrid composites. Addition of *Alkaline Earth Metal* (Mg) during the synthesis process have led to the exploration of some interesting results from the uniaxial tensile loading tests.

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 cry-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 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].

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)

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. 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.

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*.

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

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). 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]. 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 ^oC to ensure complete liquification of Aluminum. The ceramic particle reinforcement (SiC and B_4C) was pre-heated in an oven (at 250 ^oC) to remove moisture content present in the particle. The pre-heated SiC and B4C 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 was poured into the pre-heated metal mould cavity (150 mm x 15 mm x 15 mm) at a temperature 400 ^oC followed by a uniform cooling in the ambient temperature.

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

5. Results and discussions:

5.1. Material characterization:

5.1.1 Optical microscopy:

The cast samples of different composition were cut into small pieces (15 mm x 20 mm x 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.1a) were detected in the matrix, whereas for the samples (S2, S3 and S4) tend to have uniform distribution (shown in Fig.1b,1c and 1d) 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.

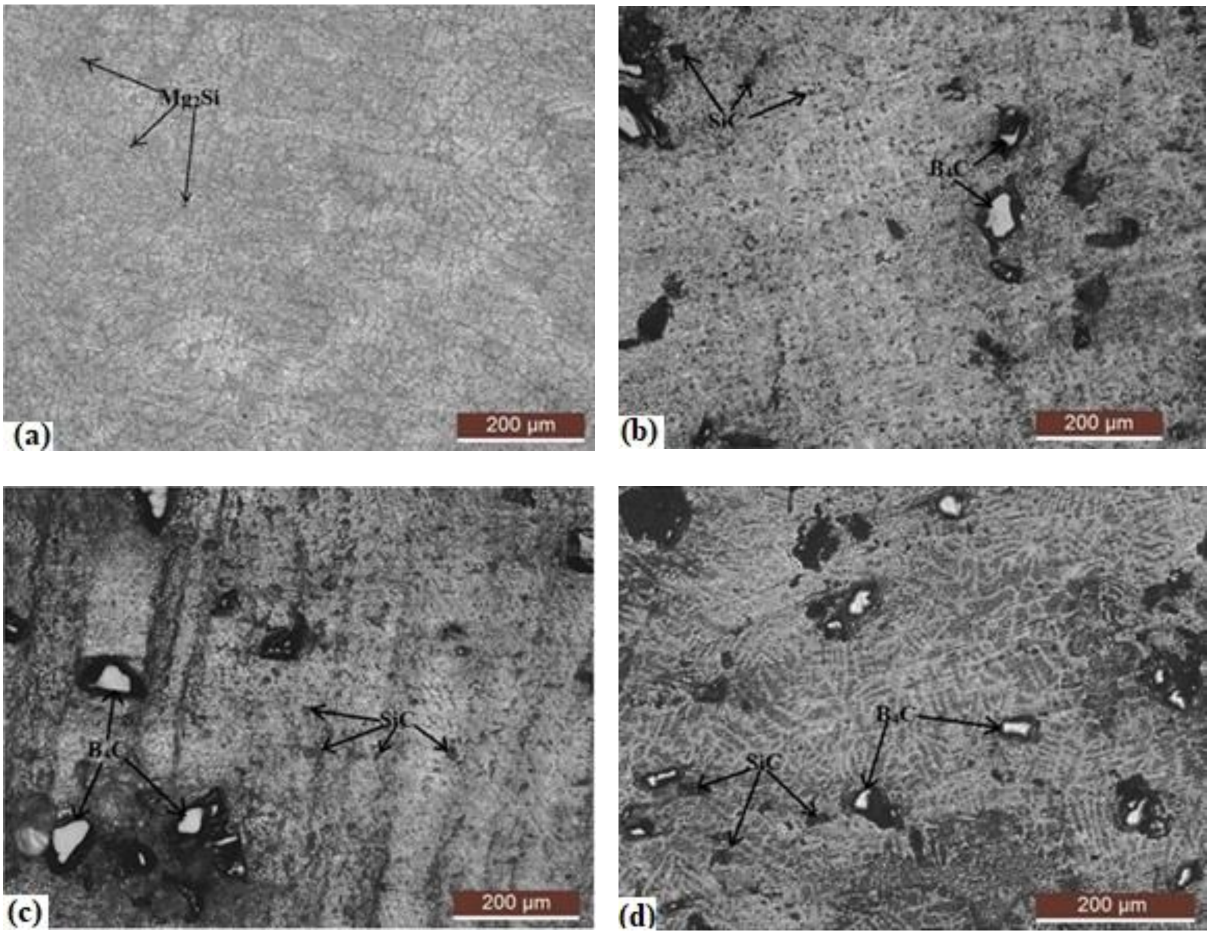


Fig 1. **(a)** Pure AA 6061 microstructure Specimen S1; **(b)** 4 wt.% SiC and 2 wt.% B_4C hybrid composite microstructure specimen S2; **(c)** 3 wt.% SiC and 3 wt.% B_4C hybrid composite microstructure specimen S3; and **(d)** 2 wt.% SiC and 4 wt.% B_4C hybrid composite microstructure specimen.

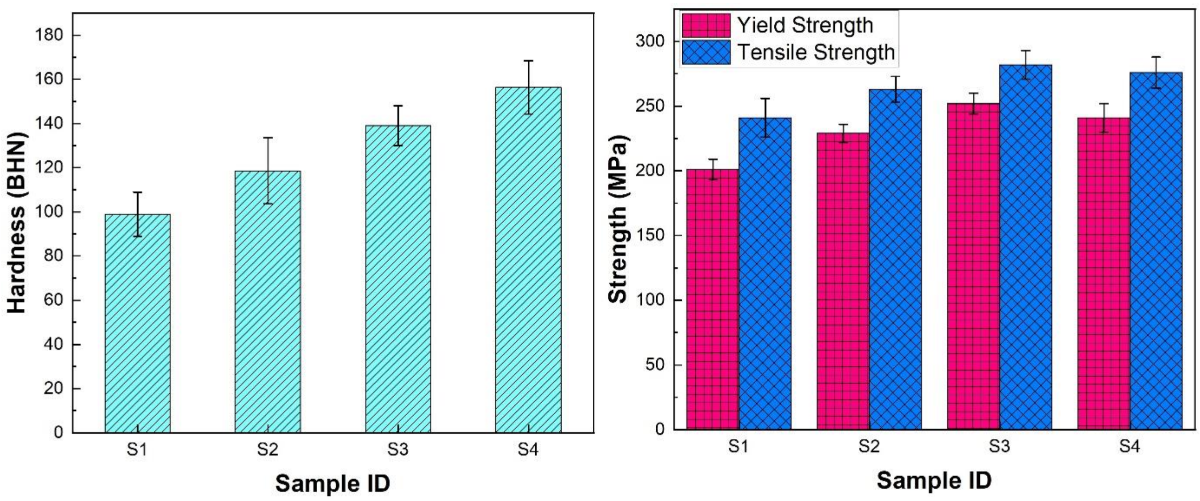
5.1.2 Indentation test results of AA6061 hybrid composites:

The bulk hardness of the mounted samples (S1-S4) was experimentally calculated using Brinell Hardness Scale. The test results (shown in Fig.2a) 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.3b), 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

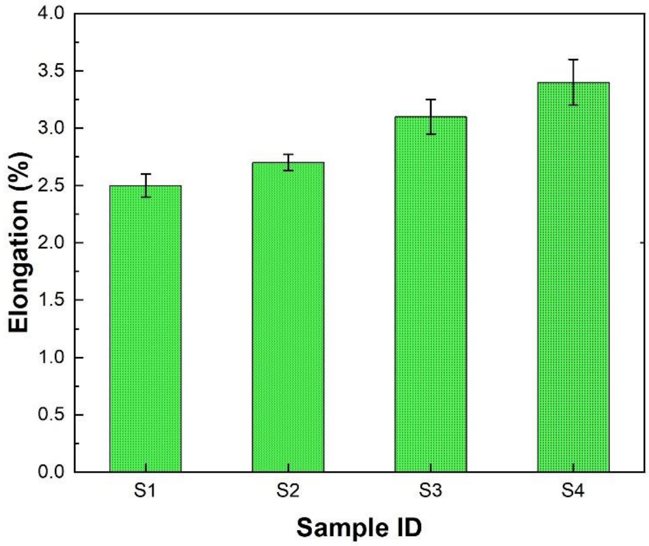
(shown in Fig.3d) value with increase in SiC (wt.%) [28]. In the present investigation, the SiC wt.% for the samples (S2-S4) was replaced with the B_4C wt.% to maintain a fixed reinforcement and the addition of the hard B_4C particles have helped in compensating the effect of SiC that is responsible for increase in hardness of majority of hybrid composite (AA6061/SiC). Except one recent study (shown in Fig.3b) by a group of researcher lead by *Hynes et. al., 2020* [29], almost all work showed an 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.

5.1.3 Uniaxial tensile test results of AA6061 hybrid composites:

The tensile tests were conducted on cylindrical as-cast AA6061 hybrid composite based on ASTM-E-8M 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-existing crack during machining [33]. The UTS and yield strength of all the samples (S1-S4) is shwon in Fig.2b, 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.2c) for the hybrid composites (S2-S4) shown continious improvement compared to the base alloy (AA6061).



(a) (b)



(c)

Fig 2. (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.

The Ultimate Tensile Strength of AA6061/B_4C composites generally increases with the increase in both the B_4C wt.% (shown in Fig.3a) [10],[21],[30-31],[34] and B_4C vol. % (shown in Fig.3c) [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 inccreases 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].

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

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

Where, σ_m= Strength of metal matrix (MPa)

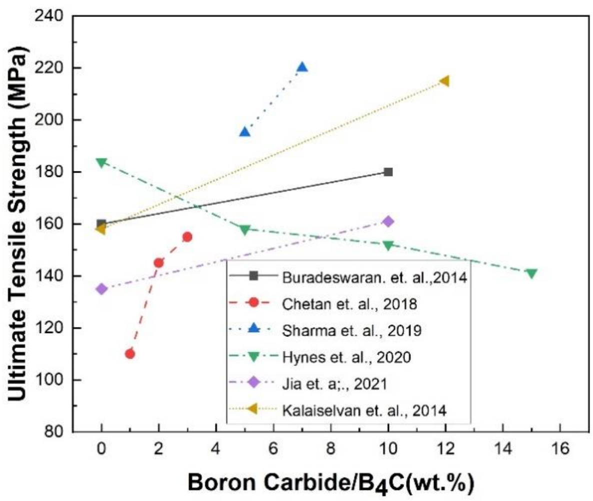
σ_r = Strength of reinforcement (MPa)

V_m = Volume of matrix

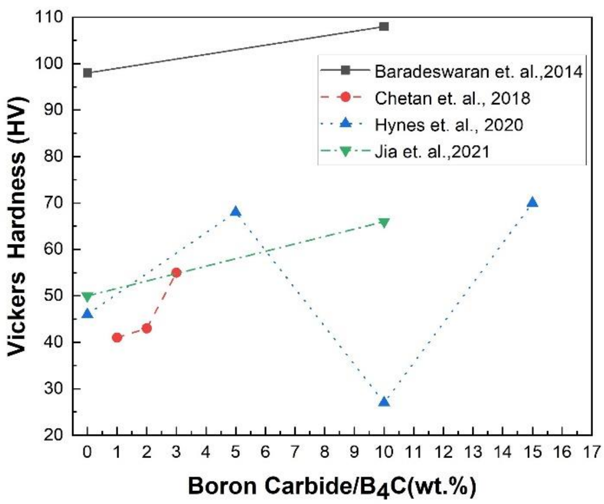
V_r = Volume of reinforcement

V_c = Volume of cluster

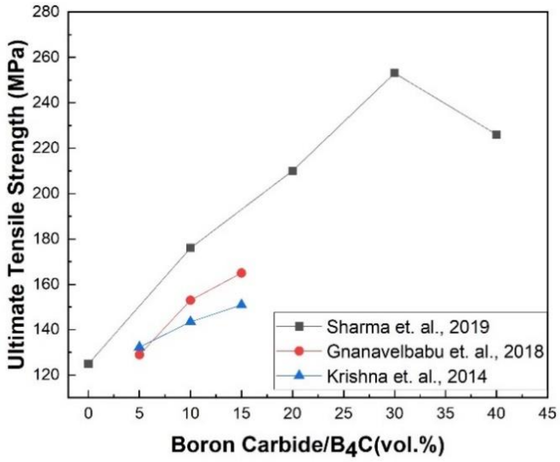
The present investigation has created a scope for studying on achieving best mechanical properties with optimized particle reinforecement to the Al base metal, because it is difficult to avoid any deletirious effect of excessive particle reinforcement on the strength of hybrid composites. This can be proven through the "Theory of Clustering", where *Hong et. al., 2003* tried to explain by comparing the theoretically calculated strength (shown in equation 1) with experimentally investigated sterength [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 equation 2.



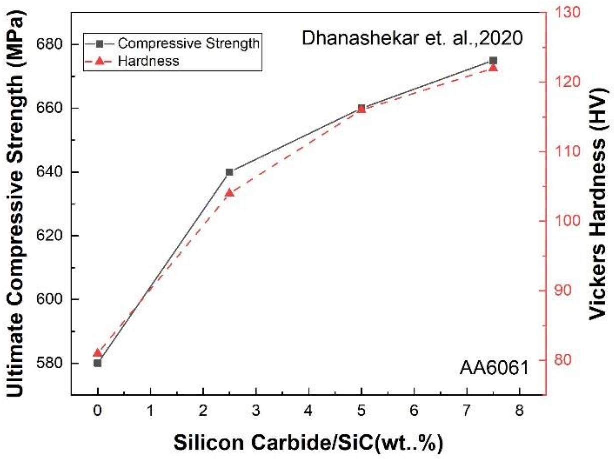
(a)



(b)



(c)



(d)

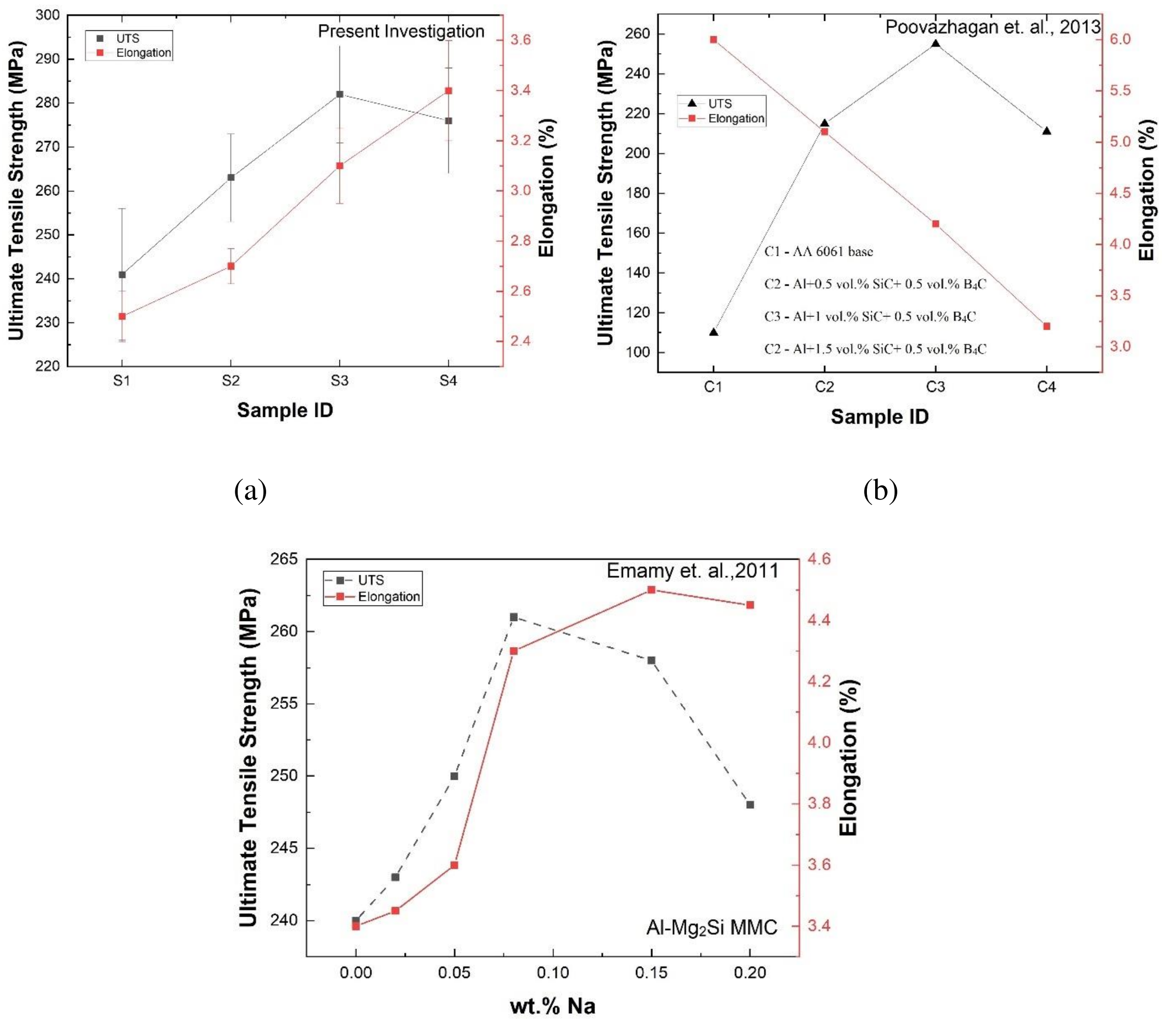
Fig 3. (a) Effect of B_4C/boron carbide (wt.%) addition on Ultimate Tensile Strength; **(b)** Effect of B_4C/boron carbide (wt.%) addition on hardness; **(c)** Effect of B_4C/boron carbide (vol.%) addition on Ultimate Tensile Strength; **(d)** Compressive Strength and hardness of AA6061/SiC composite with increasing SiC wt.%.

6. Effect of Mg addition on elongation of AA6061/ B_4C/ SiC hybrid composite:

When comparisons were done on the UTS and Elongation of AA/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 differeing with 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.4a) in the elongation (%) of hybrid compsite samples (C1-C4),whereas in the present investigation, the increase in B_4C wt.% by keeping the SiC wt.% has led to an increase (shown in Fig.4b) 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 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.4c) 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.



(a) (b)

(c)

Fig 4. 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.

7. Conclusions:

There many takeaways from this study and some interesting outcomes are highlighted as a positive outcome form this study.

(a) AA6061/B_4C/SiC hybrid composite with 6 wt.% particle reinforcement has shown better hardness properties compared to other AA6061 based hybrid composite with either SiC or B_4C reinforcement (more than the wt.% for present investigation).

(b) The yield strength of the hybrid composites is also equivalently better compared to the previously tried composition.

(c) And the most interesting among all the properties are the improved UTS and elongation values of the AA6061 hybrid composite with higher reinforcement (B_4C) content. The improvement in these properties might be due to the 0.5 wt.% Mg addition during the synthesis of the composite that has refined the Mg_2Si phase in the composite matrix. But thorough investigation needs to be done for such claim.

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

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.

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

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

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.

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.

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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Figures

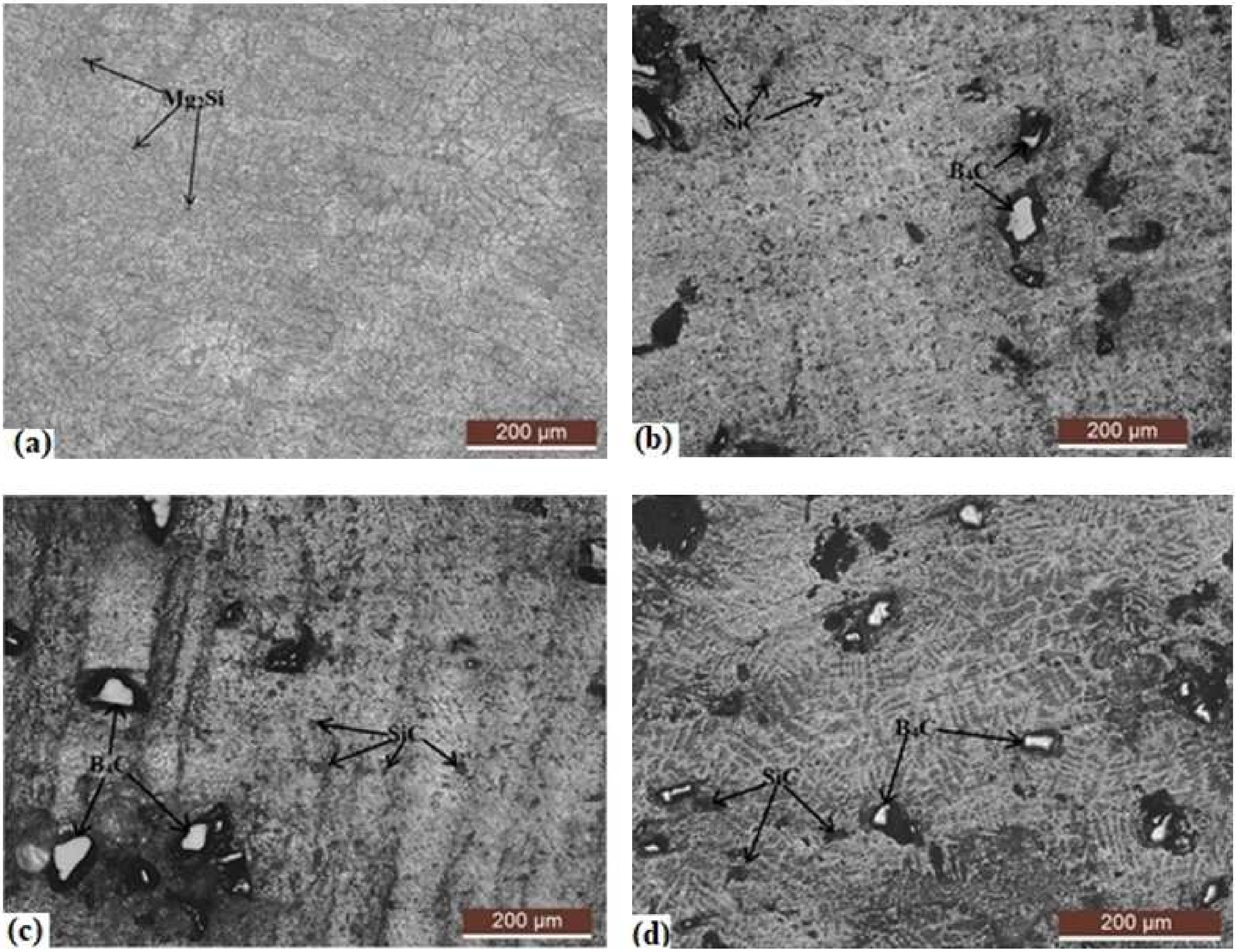

Figure 1

(a) Pure AA 6061 microstructure Specimen S1; (b) 4 wt.% SiC and 2 wt.% B4C hybrid composite microstructure specimen S2; (c) 3 wt.% SiC and 3 wt.% B4C hybrid composite microstructure specimen S3; and (d) 2 wt.% SiC and 4 wt.% B4C hybrid composite microstructure specimen.

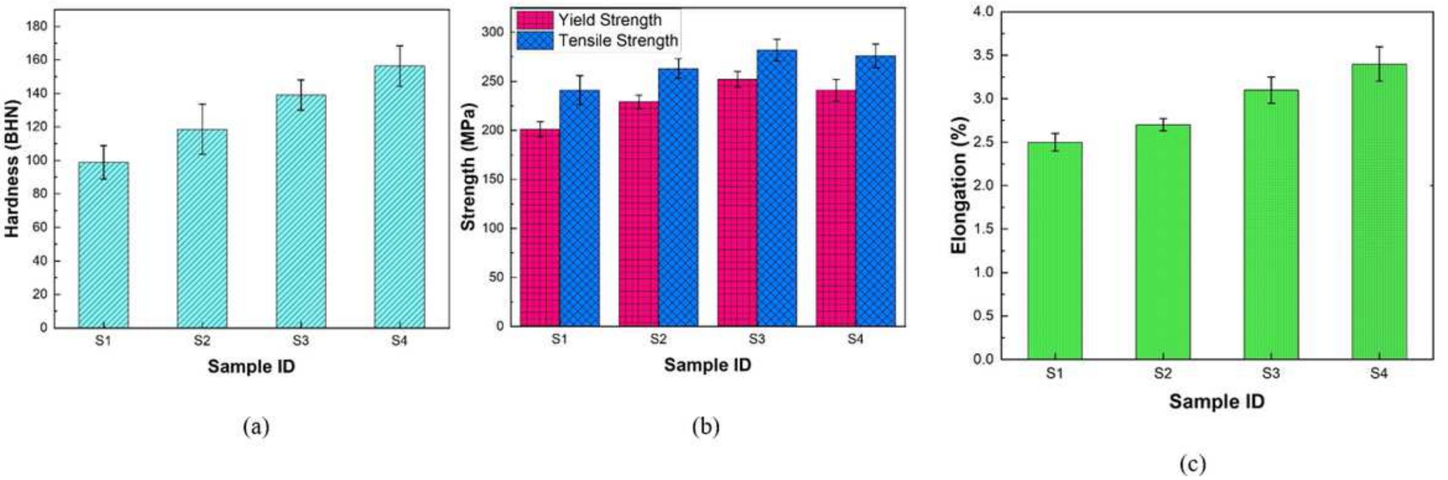

Figure 2

(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 B4C and SiC.

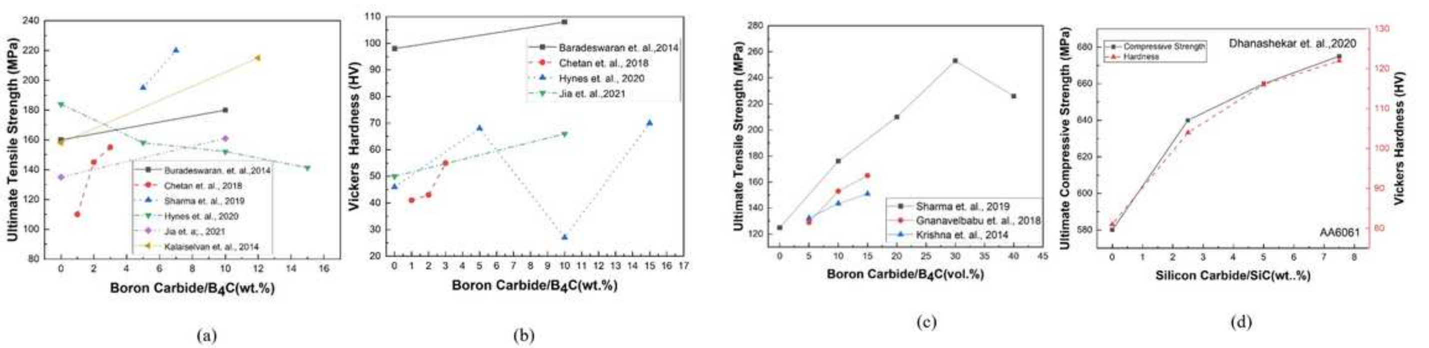

Figure 3

(a) Effect of B4C/boron carbide (wt.%) addition on Ultimate Tensile Strength; (b) Effect of B4C/boron carbide (wt.%) addition on hardness; (c) Effect of B4C/boron carbide (vol.%) addition on Ultimate Tensile Strength; (d) Compressive Strength and hardness of AA6061/SiC composite with increasing SiC wt.%.

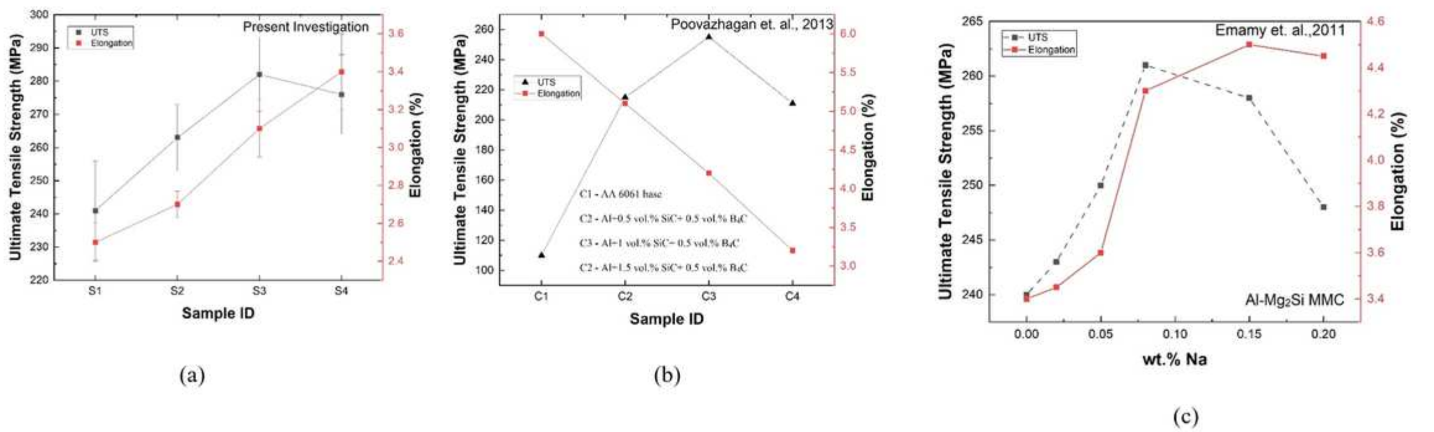

Figure 4

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.