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Original Article

Influence of B_4C and industrial waste fly ash reinforcement particles on the micro structural characteristics and mechanical behavior of aluminium (Al–Mg–Si-T6) hybrid metal matrix composite

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The expectations over composite materials have been increased especially in automotive and aerospace applications due to its high strength to weight ratio and good mechanical properties. Here, we aim to fabricate a hybrid composite of high strength and low density for automotive application to suits the above needs. In this investigation, the heat-treated aluminum alloy Al–Mg–Si-T6 was initially reinforced with industrial waste fly ash particles at five different weight fractions of 0%, 5%, 10%, 15% and 20%, respectively by stir casting process. The mechanical properties such as tensile strength, compression strength, hardness and density were tested, and microstructure of the composite was evaluated to explain the mechanical properties evolution. From the results, it was concluded that the composite with 10% fly ash shows enhanced at maximum the properties when compared to others. Then, the Al–Mg–Si-T6 – 5% fly ash was further reinforced with boron carbide particles by using three different fractions of 2.5%, 5% and 7.5%, respectively by stir casting process. The microstructural analysis, Scanning Electron Microscope analysis (SEM) and Energy Dispersive X-ray Spectroscopy analysis (EDS) were carried out for the casted samples to evaluate interfacial bonding, agglomeration, clustering and void formation in the hybrid composite samples. The casted samples were also tested for mechanical properties such as tensile strength, compression strength, hardness and density. It reveals that the optimal combination of 10% reinforcement (5% fly ash and 5% boron carbide) shows 18.7% higher tensile strength, 11.3% higher hardness and 38.6% higher compression when compared with the unreinforced Al–Mg–Si-T6 heat treated alloy. It is expected that the

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present hybrid metal matrix composites can be adopted for the fabrication of drive shaft in race cars.

1. Introduction

Metal matrix composites (MMC) play a major role in high strength applications such as aerospace and automotive industries. In order to satisfy the continuum evolving necessities and comply with novel regulations, various properties such as mechanical and tribological properties need to be improved.

The properties of the MMC can be improved by the incorporation of more than one element with different sizes and shapes which forms the well-known Hybrid Metal Matrix Composites (HMMC) [1]. The HMMC plays a vital role in the field high strength applications. The incorporation of more than one material with different sizes and shapes will led to the high strength to weight ratio, high resistance to wear and other superior properties.

Balasubramani Subramaniyam et al. [2] investigated the influence of B_4C and coconut shell fly ash in the aluminium metal matrix composites (Al7075); manufactured by sir casting in different weight percentage. It was revealed that the hardness, tensile strength, impact strength of the composites was increased by the adding the B4C and coconut shell fly ash. Otherwise, the hardness was increased by 33% with addition of 12% of B4C and 3% of fly ash and the tensile strength was increased by 66% with addition of 9% of B4C and 3% of fly ash. When compared to composites synthesized from the sintering technique and squeeze casting technique, stir casting was the most economical and readily available [3–5]. Generally, the aluminum matrix composites are machined by the Electric Discharge Machining [6]. Arunachalam et al., examined the dry sliding wear parameters of AA336 aluminium alloy by adding the boron carbide (10wt%) and fly ash (5wt%). The uniform distribution of the reinforced particle in AA3336 was identified by the microstructure analysis. The wear result shows that the weight loss of sample decreases with increase the sliding velocity [7]. Pratheep Reddy et al. [8] analyzed the mechanical and tribological properties of the metal matrix composite which when was added boron carbide and fly ash in different weight percentage. The composite was done by liquid metallurgy stir casting technique. The composite showed a peak enhancement in the wear resistance and hardness, when the composite particles are reinforced with 3% of boron carbide and 7% of fly ash. They used them for structural applications like turbine. Nivin Joy et al. [9] analyzed the aluminium 6061 metal matrix which reinforced with (B_4C) boron carbide, magnesium oxide and fly ash. They use boron carbide as primary reinforcement. Magnesium oxide and fly ash are secondary reinforcements to reduce the weight of the composite and enhance wettability. Various weight percentage of the reinforcements are used in the stir casting method for the composite preparation. Thus, the boron carbide, magnesium oxide and fly ash contribute to improving the mechanical properties and surface properties of aluminum 6061 metal matrix composite. Ajay Kumar et al. [10] investigated the improvement of the A356 aluminum alloy by adding graphite, boron carbide (B_4C) and fly ash using stir casting. To enhance the mechanical properties the boron carbide, graphite, fly ash were reinforced using different weight percentage (0%, 5%, 10%, 15%). Graphite is a pure form of coal with lubricant properties. The results show that aluminium alloy A356 was enhanced by the adding boron carbide (B_4C), graphite, fly ash. Microstructure analysis revealed that the reinforced particles were evenly distributed in the metal matrix composite. Tensile strength was increased by almost 60%–70%. Abhishek Bhardwaj et al. [11] explored the performance of aluminium 6063 by adding B4C and fly ash. The composite was made by stir casting applying three different levels of % reinforcement of B_4C and fly ash. The tensile strength was enhanced by increasing the wt% of B_4C while the hardness rate was reduced. Shubham Sharam et al. [12] examined the effect of adding the SiC/Muscovite in the hybrid metal matrix composite. The reinforcements were used to improving the mechanical and tribological properties of the metal matrix composite. As a result of the reinforcement with SiC/Muscovite the wear resistance, hardness, tensile strength of the metal matrix composite was improved. Kumar et al. [13] evaluated the wear behavior of the Al6082 reinforced with 5% of B4C and 5% of fly ash particles. A great enhancement of wear resistance was noticed while testing the samples. Therefore, the B_4C and fly ash reinforcement influences positively the wear behavior of the composites. Mohit Kumar Sahu et al. [14] investigated the microstructure evolution and hardness of Al7075 reinforced by of B_4C and fly ash. The various weight percentage of B_4C and fly ash in Al7075 distributed uniformly allows to enhance the hardness of the composite and prove to be better than the aluminium alloy (Al7075) itself. Sathish Kumar et al. [15] explored the progress of A356 aluminium alloy by using three levels of weight percentage of boron carbide and fly ash reinforcements embedding the stir cum squeeze casting method. The benefit was noted in superior mechanical behavior and tribological properties of novel composite manufactured. Antaryami Mishra et al. [16] reinforced pure aluminium matrix with fly ash and silicon carbide at 3 different weight fractions using stir casting. The composite of pure aluminium reinforced with 5% silicon carbide and 15% fly ash exhibited better results when compared to the other two weight fractions. The optical micrograph showed information about the distribution of reinforcements of fly ash and silicon carbide. Jithin Jose et al. [17] reinforced the Al7075 matrix with fly ash and zirconium silicate at 3 different weight fractions using stir casting. The tensile strength and hardness were high for the novel Al7075

Table 1 – Composition of Al–Mg–Si-T6 heat treated alloy [7].

Cu	Si	Mg	Mn	Fe	Ti	Zn	Al
0.15-0.4	0.4-0.8	0.8-1.2	Max0.15	Max0.7	Max0.15	Max0.25	Balance

composite matrix containing 3% Zirconium Silicate and 6% fly ash. The wear rate and coefficient of friction were also less for this composite. However, there was noted that the impact energy remain almost the same. Senthilkumar G et al. [18] reinforced the LM6 matrix with boron carbide and fly ash at 3 different weight fractions using stir casting. The coefficient of friction and wear loss increased with the increase in the reinforcement percentage. Yet, the hardness decreased with the increase in boron carbide and fly ash percentage. Muruganandhan et al. [19] reinforced the Al7075 matrix with fly ash and titanium carbide at 3 different weight fractions using stir casting. The tensile test results indicated as much as 32% increase in the tensile strength of the reinforced Al7075 compared to unreinforced Al7075. Hardness of the reinforced Al7075 was also 40% greater than that of the unreinforced Al7075. However, beyond 10% addition of fly ash the mechanical properties started decreasing because of transition to brittle phase. Jayakumar J et al. [20] reinforced the LM25 matrix with fly ash and boron carbide at 3 different weight fractions using stir casting. It was concluded that wear rate and co-efficient of friction decreases with increasing the volume content of the reinforcement. Jayaram et al. [21] reinforced the aluminium with fly ash and boron carbide at 3 different weight fractions by powder metallurgy technique. The samples of 30% boron carbide with 10% fly ash exhibited low density and high hardness. Chandramohan V et al. [22] reinforced Al359 with fly ash, graphite and boron carbide at 3 different weight fractions by stir casting process. The sample with 5% graphite, 5% boron carbide and 15% fly ash exhibited good tensile strength and hardness. Sharanabasappa R Patil et al. [23] reinforced the LM25 matrix with fly ash and alumina at 3 different weight fractions using stir casting. The tensile strength and hardness increased with the increase in addition of alumina. But ductility and impact strength got reduced with increase in reinforcement percentage. Gopal Krishna et al. [24] reinforced the AA6061 matrix with vary size of boron carbide at 4 different weight fractions using stir casting. The hardness was found highest for the 12% weight fraction of boron carbide sample having a size of 105 μm and the tensile strength was highest for the 8% weight fraction of boron carbide. Poovazhagan et al. [25] reinforced the AA6061 matrix with Nano silicon carbide and nano boron carbide at 3 different weight fractions using ultrasonic cavitation-based solidification process. The SEM and EDS analysis proved the presence of the reinforcements. The tensile strength and hardness increased with the increase in boron carbide percentage while the impact strength decreased. Arun et al. [26] reinforced AA6061 matrix with silicon carbide and fly ash at 3 different weight fractions using stir casting process. The tensile strength and fatigue life increased with the increase in fly ash percentage. The SEM analysis revealed the fly ash and silicon carbide distribution. Rama Rao et al. [27] reinforced the LM6 matrix with boron carbide at 3 different weight fractions using stir casting. The compression strength and hardness increased with the increase in boron carbide percentage while the density decreased. The SEM analysis revealed the reinforcement distribution and the XRD pattern proved the presence of boron carbide. Anilkumar et al. [28] reinforced the AA6061 matrix with varying sizes of fly ash at 3 different weight fractions using stir casting. The tensile strength, compression strength and hardness increased with the increase in the weight fraction of reinforced fly ash and decreased with the increase in particle size of the fly ash. However, for composites with more than 15% weight fraction of fly ash particles, the tensile strength was found decreasing.

In this research, the heat-treated aluminium alloy Al–Mg–Si-T6 was initially reinforced with fly ash at five different weight fractions of 0%, 5%, 10%, 15% and 20% by stir casting process and the mechanical properties such as tensile strength, compression strength, hardness and density were tested, and microstructure of the composite was revealed. From the results, it was concluded that the composite with 10% fly ash retain the better properties when compared to others. Therefore, it was chosen as the optimum reinforcement percentage. Then, the Al–Mg–Si-T6 – 5% fly ash was further reinforced with boron carbide particles considering three different fractions of 2.5%, 5% and 7.5% applying stir casting process. These cast samples were tested for mechanical properties such as tensile strength, compression strength, hardness and density. Along with these tests the microstructure, Scanning Electron Microscope analysis (SEM) and Energy Dispersive X-ray Spectroscopy analysis (EDS) were carried out for these hybrid composite samples.

2. Materials and methods

2.1. Materials

For the fabrication of the metal matrix composites (MMC) and hybrid metal matrix composites (HMMC), Al–Mg–Si-T6 heat treated aluminium alloy was chosen as the matrix material and fly ash and boron carbide was chosen as the reinforcement materials. The MMC and HMMC was fabricated with the help of stir casting technique [29].

Al–Mg–Si-T6 is a precipitation hardened aluminum alloy, containing magnesium and silicon as major alloying element [30]. It has good mechanical properties, exhibits good weldability and it is one of the commonly used aluminum alloy for the high strength applications [31]. The composition of Al–Mg–Si-T6 is given in the Table 1.

Fly ash possesses low density and it is generally spherical in shape and range in size from 0.5 μm to 300 μm. Hence, it can be used as reinforcement in composite materials [32]. Fly ash is available abundantly as it is an industrial waste. The general composition of fly ash is given in Table 2.

Table 2 – Fly ash composition.

Compounds	SiO_2	Al_2O_3	Fe_2O_3	CaO	L.O.I
Percentage %	15–45	20–25	4–15	15–40	0–5

Boron carbide is a material whose melting point is about 2700 °C with high hardness, high cross section for absorption of neutrons, stability to ionizing radiation and most chemicals [33]. Its vickers hardness (38 GPa), elastic modulus (460 GPa) and fracture toughness (3.5 MPa $m^{1/2}$) approach the corresponding values for diamond (1150 GPa and 5.3 MPa $m^{1/2}$). Hence boron carbide is called as black diamond. It is denoted by B_4C. In this research, boron carbide with the particle size of 63.35 μm which has the purity percentage of 91.26% were adopted. The incorporation of boron carbide with the fly ash in the Al–Mg–Si-T6 heat treated alloy allows to form the hybrid metal matrix composites (HMMC) [34].

2.2. *Methods*

Stir casting method has employed for the fabrication of the metal matrix composites in which the reinforcement particles were dispersed in this molten aluminium with the help of stirring action. The stir casting process is the simplest and more effective methods when compared with other liquid state fabrications [35]. The samples were casted by the conventional casting methods and then further carried out for the machining based on the standards required for the testing [36].

The schematic flow chart of the methodology was shown in Fig. 1. Initially, 5 samples of metal matrix composites were prepared with the unreinforced sample of pure Al–Mg–Si-T6 and other samples of Al–Mg–Si-T6 reinforced with 5%, 10%, 15%, and 20% of fly ash respectively. The composite reinforced with fly ash was optimized based on the properties such as tensile strength, compressive strength, hardness and density [37]. Then, Al–Mg–Si-T6 was reinforced with 3 different weight fractions, 2.5%, 5% and 7.5% of boron carbide along with the optimized 5% fly ash composition. The different weight fractions of the normal metal matrix composite and hybrid metal matrix composite are shown in Tables 3 and 4 respectively.

The metal matrix composite and hybrid metal matrix composites were fabricated by stir casting route [38]. At the beginning, the crucible preheating temperature of 540 °C for 35 min was adopted [39–51]. The Al–Mg–Si-T6 heat treated aluminium rods was placed inside the crucible of the induction furnace and the crucible was gradually heated up to a maximum of 750 °C [34]. The fly ash and boron carbide were separately preheated in a muffle furnace to a maximum of 500 °C to remove the moisture content present in it [40]. Once after the Al–Mg–Si-T6 alloy had melted, the preheated fly ash and boron carbide were added to it. The 45° blade angle stirrer which was made of Inconel was immersed in the molten aluminum at the position of 40% from the base and the stirring was performed with the rotational speed was about 250–300 rpm with the holding time of 10 mins. The stir casting specifications are stirrer speed (0–350) rpm, capacity of the melting pot - 1 kg of aluminum (max), maximum operating temperature 900 °C, operating voltage 440 V with AC three Phase 50 c/s, app. power consumption 4 KW, preheating furnace temperature 800 °C and control automatic by microcontroller. In order to remove the slag in the mixture of aluminium with fly ash and boron carbide, cover flux was used. It removes the slag and helps in proper dispersion. After stirring, the molten metal was poured into the mould for solidification [41]. The diameter of the mould was 20 mm and the depth was 200 mm. Another mould of 30 mm diameter and 100 mm depth was used for pouring the excess molten metal. Similarly this process was repeated for different weight fractions [42]. Different stages of stir casting are shown from Fig. 2.

After the fabrication of the composite, it was machined according to the ASTM standards to carry out the tests [43]. The tensile test, compression test, hardness test, density measurement and microstructure study were carried out for all the composite samples [44]. Whereas, scanning electron microscope analysis (SEM) and energy dispersive X-ray spectroscopy analysis (EDS) were carried out exclusively for the hybrid composite with reinforcements of fly ash and boron carbide.

The Tinius Olsen Computerized Universal Testing Machine, H50KL model was used to find the tensile properties for the cast specimens. The specimens were prepared according to ASTM standards. The overall length was 90 mm and the gauge length was 40 mm. The specimen diameter was 5 mm. The feed rate was 2 mm/min. The compression test was carried out in the universal testing machine. The specimens were prepared according to ASTM standards [45]. The gauge length was 40 mm and the specimen diameter was 15 mm. The feed rate was 2 mm/min. Hardness was calculated in terms of Rockwell B scale number. The indenter used was 1/16″ steel ball. The maximum load applied was 15 kg. Density was calculated by finding the mass and volume of each specimens and thereby finding their ratio [46]. The microstructure analysis was done by optical microscope and the moulds with specimens were prepared for all eight weight fractions and the images were taken at 100× magnification. The SEM and EDS analysis were done exclusively for the hybrid composite with fly ash and boron carbide reinforcements. The SEM images were taken at different magnifications ranging from 200× to 1500× and the EDS analysis was also done using the SEM images taken. The mapping of the SEM images was also done to find the presence of the reinforcements.

3. Results and discussion

3.1. *Microstructural analysis*

The microstructure analysis was done by optical microscope and the specimens were prepared for all eight weight fractions and the images were taken at 100× magnification. The Fig. 3 (a) shows the optical microscope image of pure Al–Mg–Si-T6 alloy without the reinforcement of fly ash. It also shows the fine grained primary aluminium particles. Few voids are visible in the microstructural image of the casted sample 1 and also the grain structure was clearly observed. The Fig. 3 (b) shows the optical microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash. The optical microscope

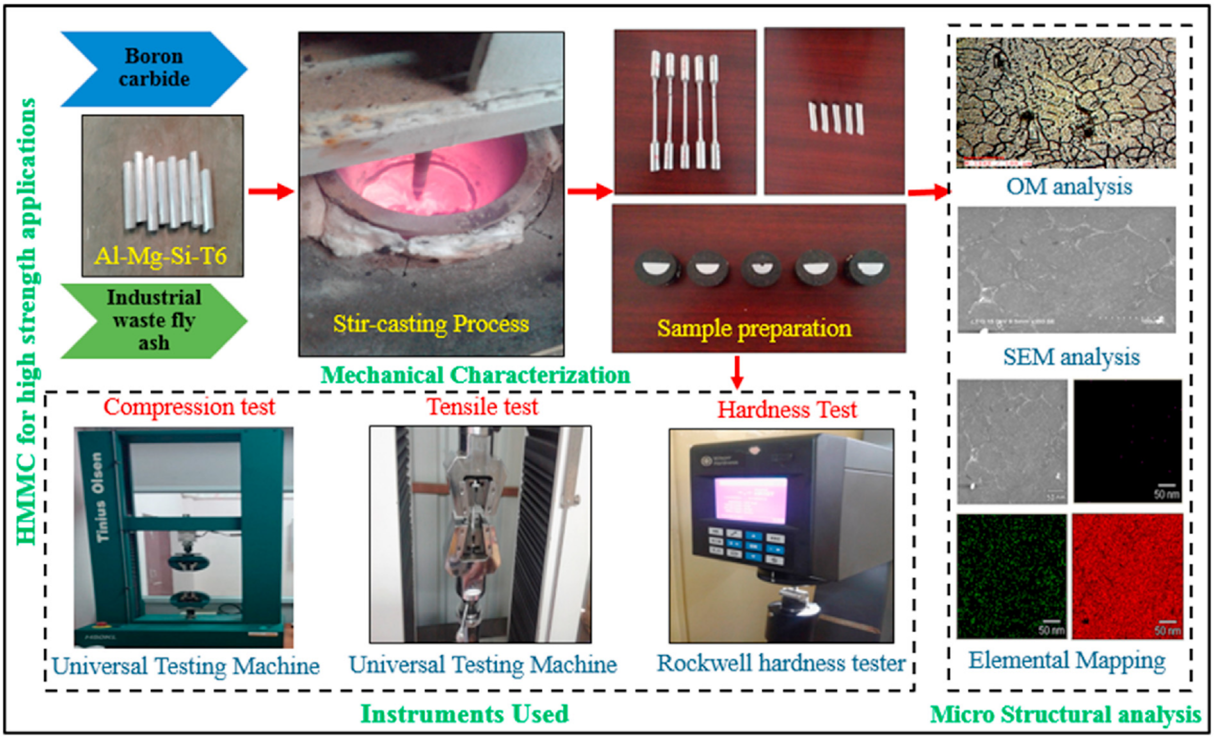

Fig. 1 – Schematic flow chart of the methodology.

image shows the uniform distribution of fly ash reinforcement particles which was present all along the casted specimen. It also shows the presence of some of the isolated particles that have occupied the grain boundaries. These isolated reinforcement particles may disturb the formation of small and fine grains. The Fig. 3 (c) shows the optical microscope image of Al–Mg–Si-T6 alloy with 10% reinforcement of fly ash. The image shows the formation of grains in dendritic manner. In some places, the reinforced fly ash has got agglomerated instead of dispersing. In other places the fly ash has been equally distributed over the matrix Al–Mg–Si-T6 alloy. The Fig. 3 (d) shows the optical microscope image of Al–Mg–Si-T6 alloy with 15% reinforcement of fly ash. The image shows the presence of fly ash reinforcement particles along the grain boundaries. The settling of fly ash reinforcement particles were clearly observed in the gain boundaries, this was mainly due to the addition of more amount of reinforcement particles which will consecutively leads to the reduction of the overall strength of the composite [47]. The Fig. 3 (e) shows the optical microscope image of Al–Mg–Si-T6 alloy with 20% reinforcement of fly ash. From the image, it was clear that the incorporated fly ash reinforcement particles have got agglomerated and also forms a clusters at some places. Because of this agglomeration, the formation of grains has been stopped. Hence the strength of the composite got reduced and also the grains are irregular in size. The Fig. 3 (f) shows the optical microscope image of Al–Mg–Si-T6 alloy -T6 with 5% reinforcement of fly ash and 2.5% reinforcement of boron carbide. The microstructure reveals the proper grain formation and it also shows the uniform distribution of the incorporated reinforcement particles. The Fig. 3 (g) shows the optical microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 5% reinforcement of boron carbide. The microstructure shows the dendritic grain formation with the reinforcements agglomerating at some particular places and also lumping of reinforcements was observed. The Fig. 3 (h) shows the optical microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 7.5% reinforcement of boron carbide. The microstructure reveals the grain formation in irregular manner and also more clustering was observed. This was mainly due to the reinforcement percentage exceeds the optimal combination percentage of 10% (5% fly ash and 5% boron carbide). These kinds of defects can affects the mechanical properties of the composite.

Table 3 – Weight fractions of the Metal Matrix Composite.

Sample	Al–Mg–Si-T6		Fly ash	
	Weight %	Weight (g)	Weight %	Weight (g)
1	100	1500	0	0
2	95	1425	5	75
3	90	1350	10	150
4	85	1275	15	225
5	80	1200	20	300

3.2. *SEM analysis*

The scanning electron microscope (SEM) analysis was done for the hybrid matrix composite only after the proper etching and polishing for clear view. The images were taken at different magnifications ranging from 100× to 1000×. The Fig. 4 (a) shows the scanning electron microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 2.5%

Table 4 – Weight fractions of the Hybrid Metal Matrix Composite.

Sample	Al–Mg–Si-T6		Fly ash		Boron Carbide	
	Weight %	Weight (g)	Weight %	Weight (g)	Weight %	Weight (g)
6	92.5	462.5	5	25	2.5	12.5
7	90	450	5	25	5	25
8	87.5	437.5	5	25	7.5	37.5

reinforcement of boron carbide. The SEM image shows the grain structure with the presence of boron carbide and fly ash at the boundaries and it shows good agreement with the Sahu et al. [14]. The Fig. 4 (b) shows the scanning electron microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 5% reinforcement of boron carbide. The SEM image shows the settlement of the reinforcement particles at the grain boundaries. The grain formation was visibly observed with the help of SEM image. The perfect bonding of fly ash and boron carbide over the Al–Mg–Si-T6 alloy matrix was revealed and also the uniform distribution of the reinforcement particles was observed. The Fig. 4 (c) shows the scanning electron microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 7.5% reinforcement of boron carbide. The SEM image reveals the presence of boron carbide particles at particular locations of the composite and also the fly ash particles were settled at the grain boundaries [48]. At some places the clustering of the reinforcement particles was also evident in which this kind of defects influences the mechanical characterization of the composites.

3.3. *EDS analysis*

The Energy Dispersive X-ray Spectroscopy (EDS) analysis was carried out for the casted hybrid matrix composite with the help of SEM images taken along with the EDS spectrum. EDS element mapping was done to confirm the presence of the reinforcement particles. The Fig. 5 shows the EDS image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 2.5% reinforcement of boron carbide. The EDS spectrum revealed

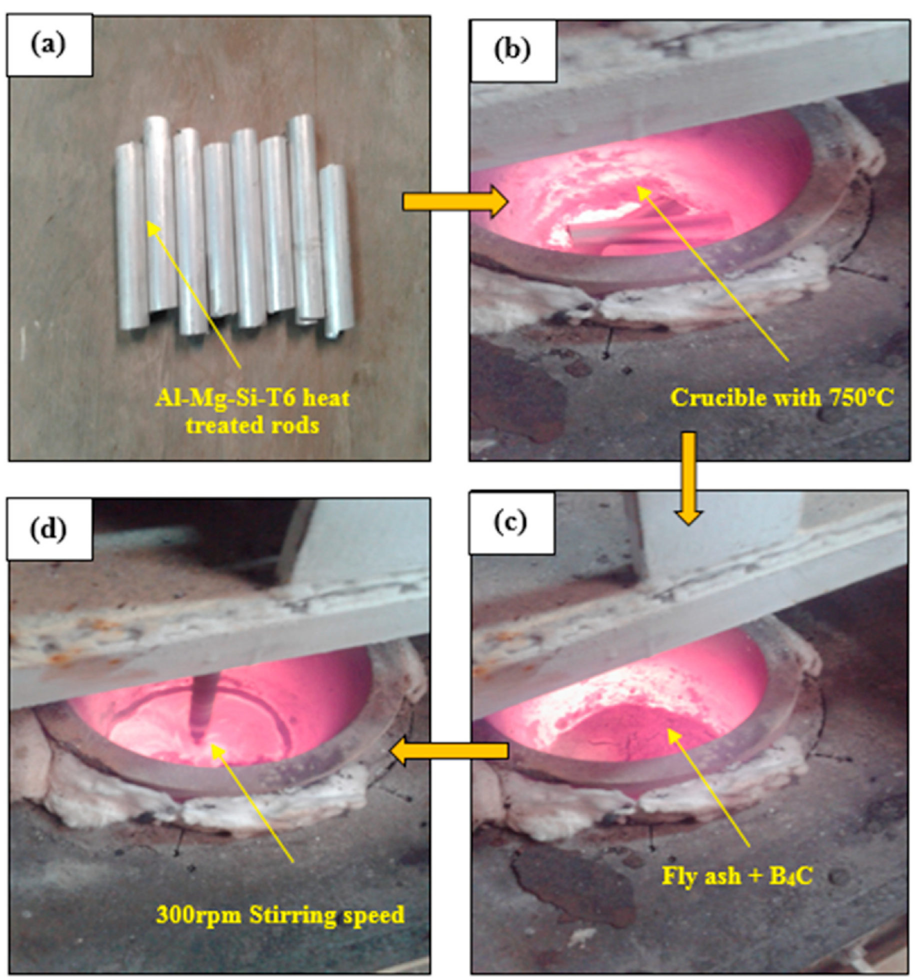

Fig. 2 – Different stages of fabrication of MMC and HMMC (a) Al–Mg–Si-T6 heat treated rods (b) Al–Mg–Si-T6 rods inside the furnace with 750 °C (c) incorporation of fly ash and B_4C (d) Stirring action with 300 rpm stirring speed.

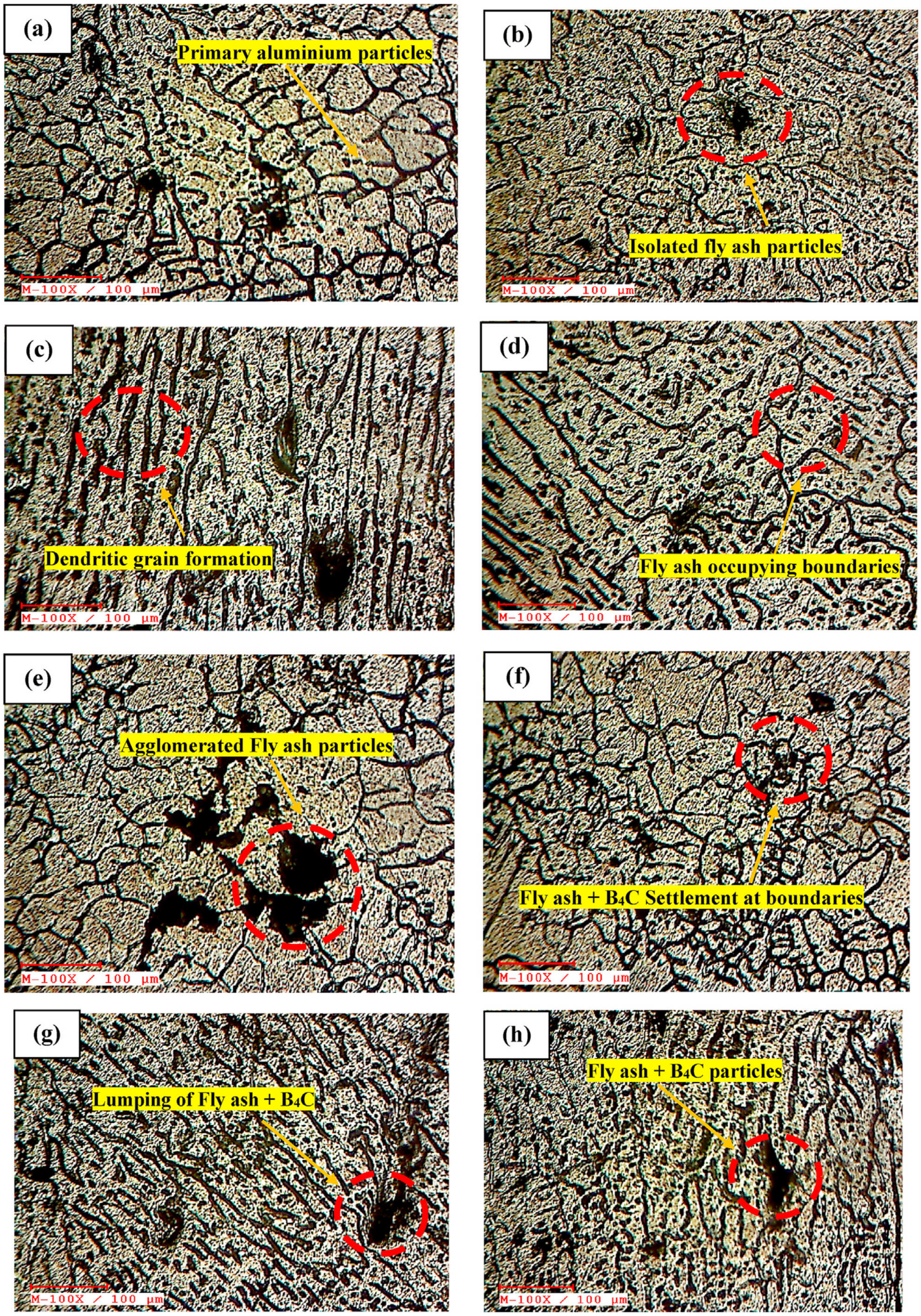

Fig. 3 – Microstructural images of (a) Al–Mg–Si-T6 heat treated alloy, (b) Al–Mg–Si-T6 alloy + 5% Fly ash, (c) Al–Mg–Si-T6 alloy + 10% Fly ash, (d) Al–Mg–Si-T6 alloy + 15% Fly ash, (e) Al–Mg–Si-T6 alloy + 20% Fly ash, (f) Al–Mg–Si-T6 alloy + 5% Fly ash + 2.5% Boron Carbide, (g) Al–Mg–Si-T6 alloy + 5% Fly ash + 5% Boron Carbide, (h) Al–Mg–Si-T6 alloy + 5% Fly ash + 7.5% Boron Carbide.

the counts of boron as zero (Fig. 8 (a)), but through EDS element mapping, the boron carbide presence was detected and it was shown in rose coloured dots. The presence of oxygen content was also revealed in the EDS spectrum. The presence of oxygen content was due to the strong affinity of metals for oxygen and so they are easily captured to the metal surface. The only way to reduce the presence of oxygen is to further heat treat the developed composite and store the sample in an air tight desiccator. Our environment is made up of oxygen so exposure of composite to the environment will naturally attract oxygen to its surface. It is possible to reduce the percentage of oxygen but it is difficult to eliminate the oxygen content completely. From the mapping images, it can be understood that the added boron carbide has settled at the

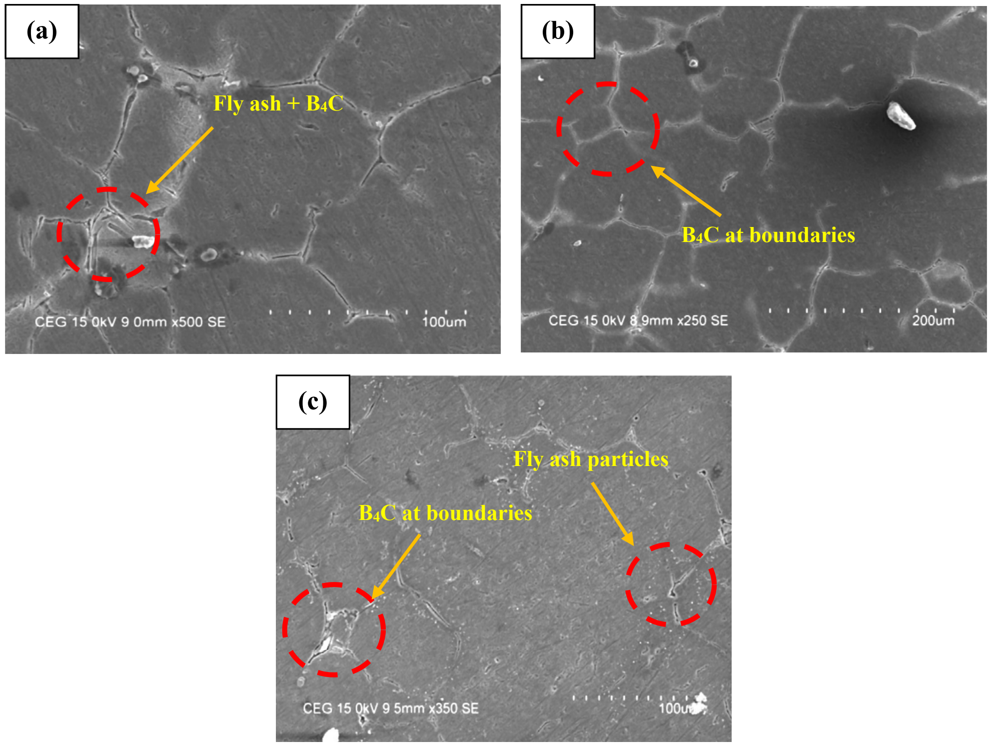

Fig. 4 – SEM images of (a) Al–Mg–Si-T6 alloy + 5% Fly ash + 2.5% Boron Carbide (b) Al–Mg–Si-T6 alloy + 5% Fly ash + 5% Boron Carbide (c) Al–Mg–Si-T6 alloy + 5% Fly ash + 7.5% Boron Carbide.

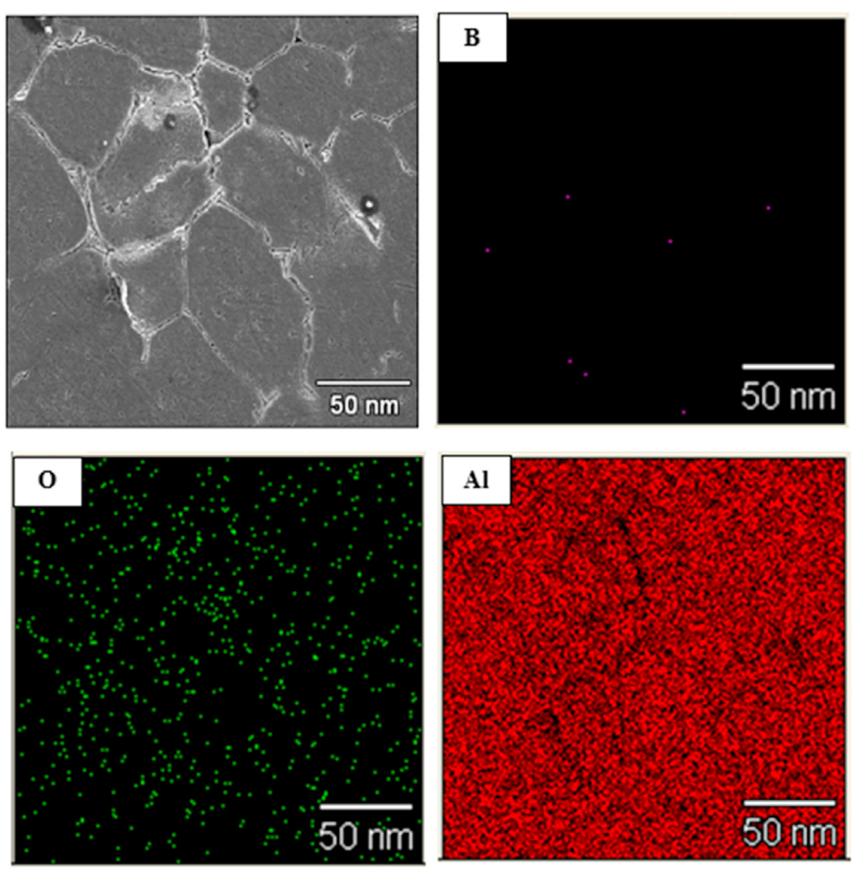

Fig. 5 – EDS images of Al–Mg–Si-T6 alloy + 5% Fly ash + 2.5% Boron Carbide.

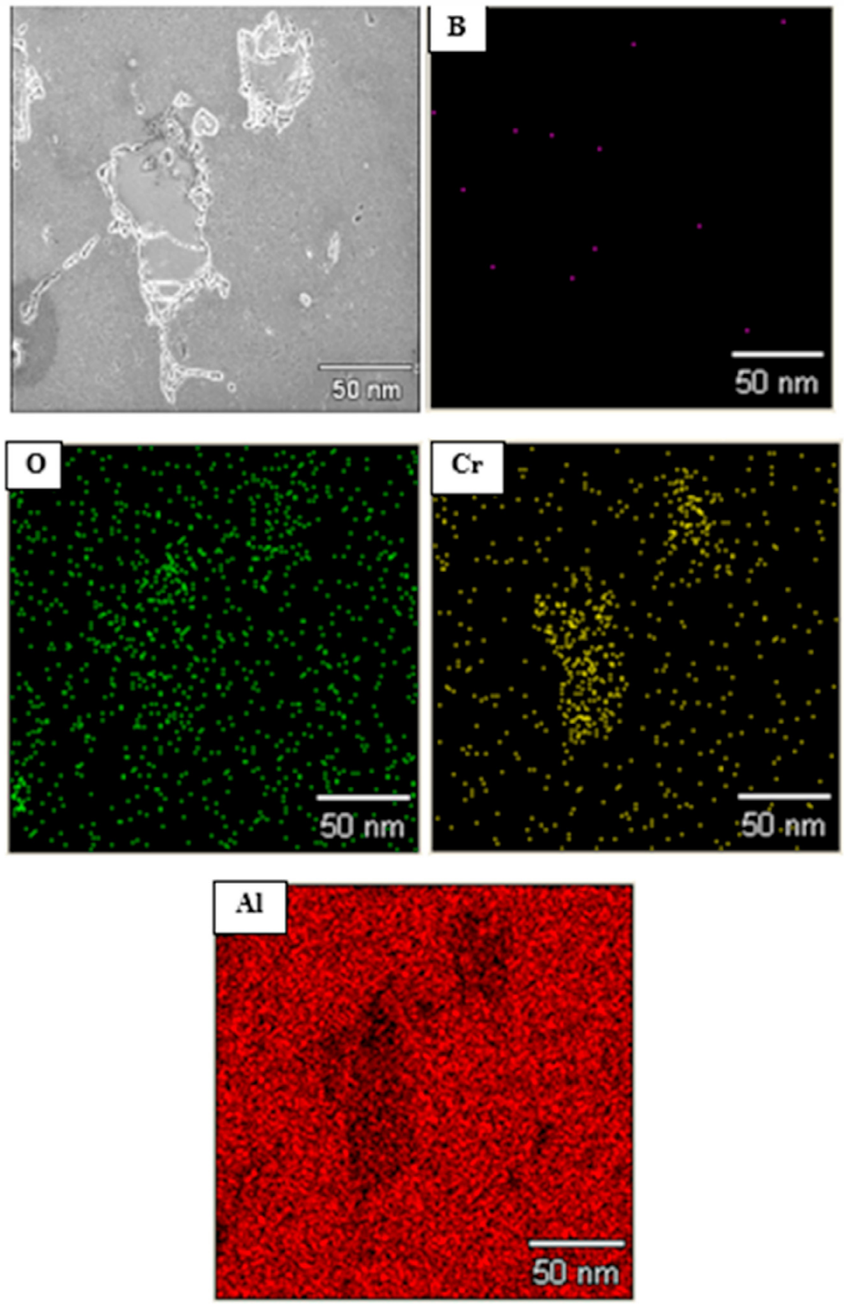

Fig. 6 – EDS images of Al–Mg–Si-T6 alloy + 5% Fly ash + 5% Boron Carbide.

grain boundaries thereby strengthening the hybrid composite [49,50]. The Fig. 6 shows the scanning electron microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 5% reinforcement of boron carbide. In this analysis, the EDS spectrum revealed the counts of boron as zero but EDS element mapping detected the presence of boron carbide and it was shown in rose coloured dots. Other than boron, silica, oxygen and chromium were also detected (Fig. 8 (b)). These elements were the components of fly ash. The Fig. 7 shows the scanning electron microscope image of Al–Mg–Si-T6 alloy with 5% reinforcement of fly ash and 7.5% reinforcement of boron carbide. In this analysis also, the EDS revealed the counts of boron carbide as zero (Fig. 8 (c)). But through mapping, the boron carbide presence was detected and it was shown in rose coloured dots. The mapping image shows that the reinforced boron carbide has equally distributed over the Al–Mg–Si-T6 alloy matrix especially at the boundaries.

3.4. *Tensile strength*

The casted tensile test samples were analysed for the tensile strength (Fig. 9). Among the cast samples with fly ash reinforcement, the sample-2 of AA6061-T6 with 5% fly ash possessed improved tensile strength of 165.53 N/mm^2 which was 6.4% higher than that of the unreinforced Al–Mg–Si-T6 alloy. From the results of the tensile test it was obtained that

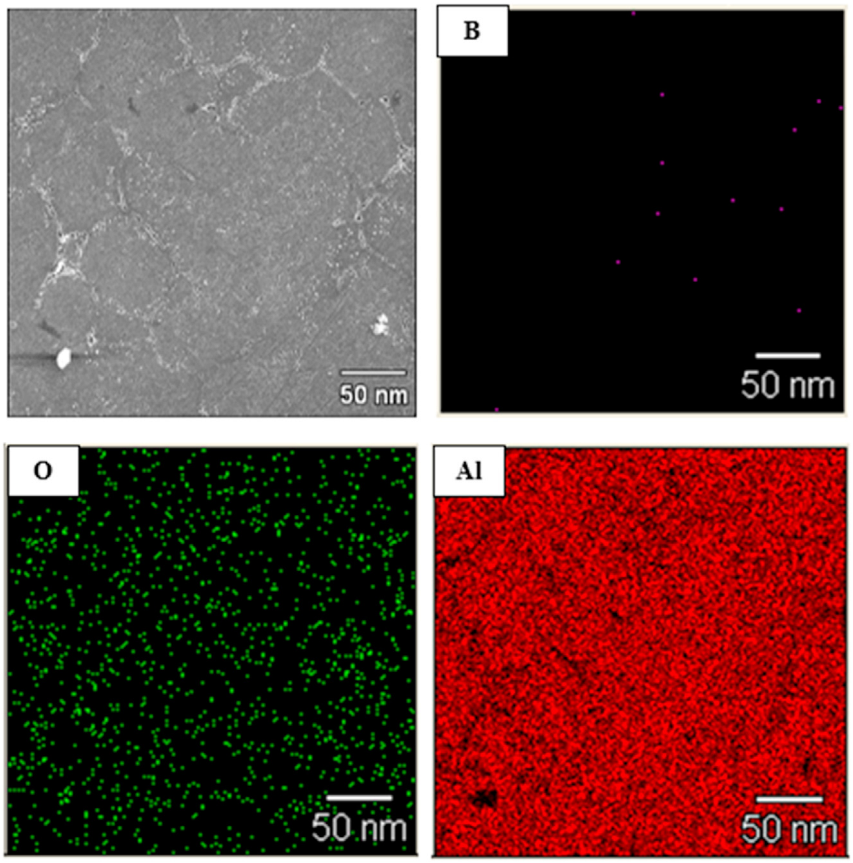

Fig. 7 – EDS images of Al–Mg–Si-T6 alloy + 5% Fly ash + 7.5% Boron Carbide.

the incorporation of 10% of fly ash shows enhanced tensile strength of 178.63 N/mm^2 and also further addition of 5% of boron carbide increases the tensile strength by 3.4%. It was evident that the addition of fly ash increases the tensile strength of the sample, it was due to the fact the presence of reinforcement particles will provide more strength to resist the deformation. It was also observed that the tensile strength increases only up to 10% of fly ash after that the strength decreases at 15% and 20% of fly ash. This was mainly due to the agglomeration of the fly ash reinforcement particles and also due to the brittle nature of the composite [51]. The superior role of brittle nature of the composites will leads to the propagation of cracks at the boundary levels of the reinforcement particles during the time of applied external loads. The presence of 2.5% of boron carbide with 5% of fly ash shows improved tensile strength of 4.9% when compared with the 20% of fly ash as reinforcement particles. This also proves that the agglomeration and clustering of the reinforcement particles plays a major role in improving the tensile strength of the composites. In the case of hybrid reinforcements of fly ash with boron carbide, the maximum tensile strength of 184.72 N/mm^2 was obtained in the combination of 5% of fly ash and 5% of boron carbide. This result also proves that the optimal combination of 10% shows enhanced mechanical properties which show good agreement with Ahamad et al. [52]. The reason lies behind the higher tensile strength of this combination was not only due to the uniform distribution of the reinforcement particles but also due to the perfect bonding of the particles with an adaptable percentage of the both the reinforcement particles. It was also noted that the tensile strength decreases by 5.2% due to the more addition of boron carbide. Even though the addition of boron carbide will helps to increase the tensile strength but the combination % (5% fly ash+7.5% boron carbide) increases beyond 10%, at that time there will be high possibility of agglomeration and clustering of particles which leads lo easy crack propagation at the grain boundary region of the reinforcement particles. So the optimal combination of 5% of fly ash and 5% of boron carbide helps to enhance the tensile strength of the composite and it was clear from the results that, beyond certain percentage of reinforcements the tensile strength started decreasing.

3.5. *Compression testing*

The casted samples were tested for compression strength (Fig. 10). From the results of the compression test, it was observed that the presence of fly ash as the reinforcement particles increases the compression strength of the composites but only up to 10% of fly ash. Among the cast samples with fly ash reinforcement, the sample-3 of Al–Mg–Si-T6 alloy with 10% fly ash possessed highest compression strength of 214.659 N/mm^2 and it was 37% higher than that of the unreinforced Al–Mg–Si-T6 alloy. After that the slight decrease of compression strength was observed, it was mainly due to the agglomeration and the clustering of the fly ash particles which was evident in the OM analysis. Compression strength of the

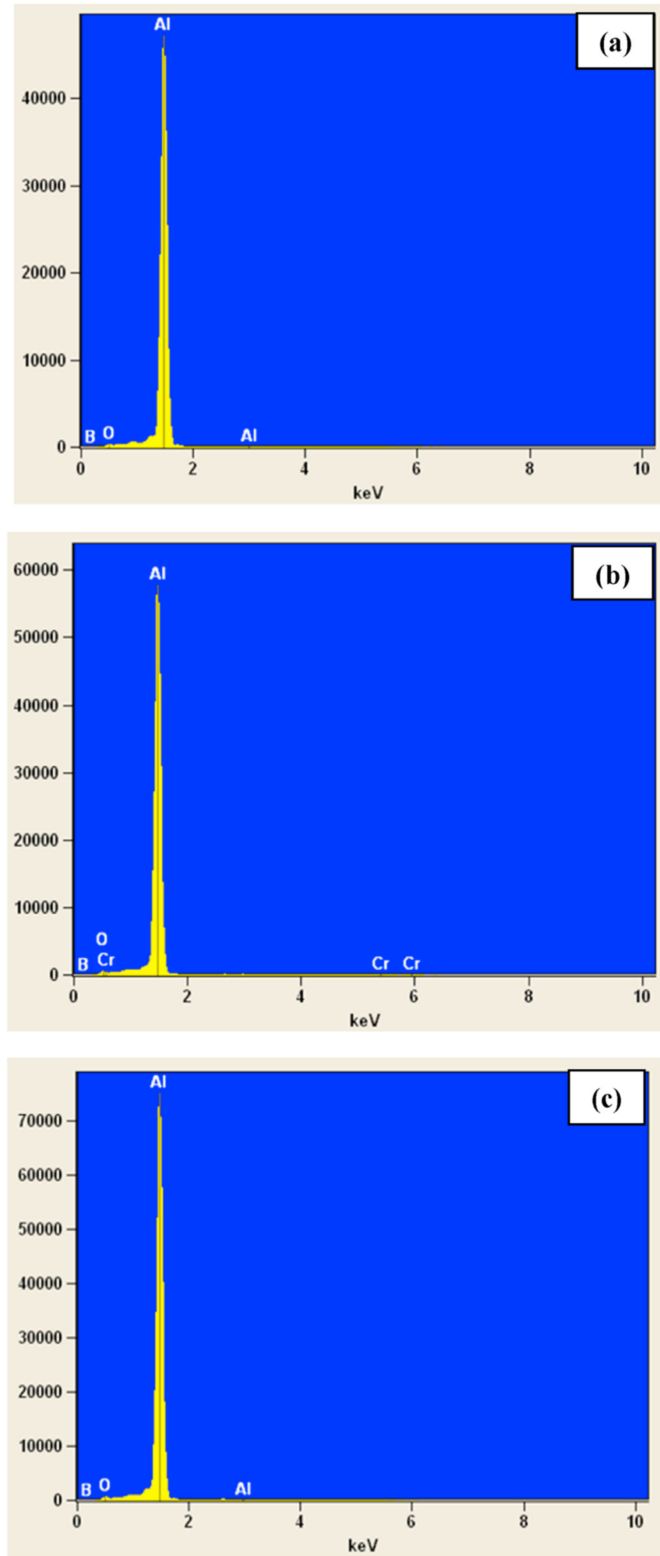

Fig. 8 – EDS elemental analysis images of (a) Al–Mg–Si-T6 alloy + 5% Fly ash + 2.5% Boron Carbide (b) Al–Mg–Si-T6 alloy + 5% Fly ash + 5% Boron Carbide (c) Al–Mg–Si-T6 alloy + 5% Fly ash + 7.5% Boron Carbide.

sample 4 (15% fly ash) decreases by 9.7% when compared with the sample 3 (10% fly ash) and Compression strength of the sample 5 (20% fly ash) decreases by 21.1% when compared with the sample 3 (10% fly ash). The presence of more amount of reinforcement particles (>10%) will leads to the agglomeration of particles which in turns creates more dislocation of reinforcement particles at the boundary region of the clustered particles [53]. In the case of hybrid reinforcements of fly

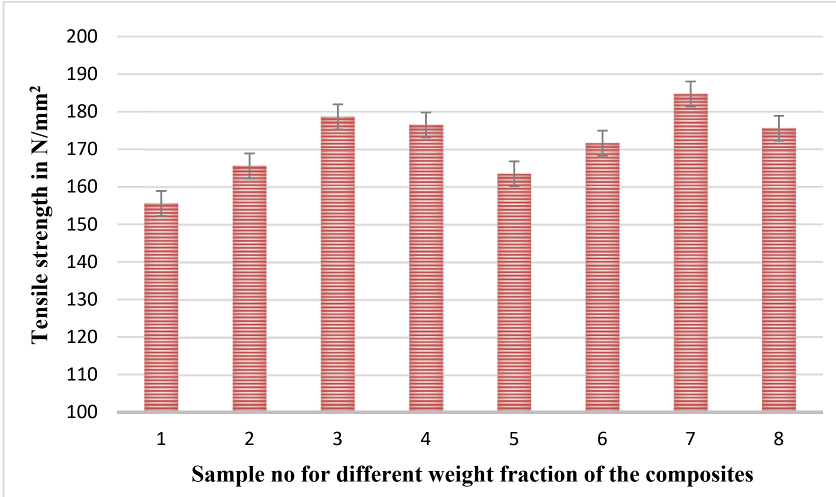

Fig. 9 – Tensile strength vs different weight fraction of the composites.

ash with boron carbide, the compression strength increased gradually with increase in boron carbide percentage but only up to optimal combination of 10% (5% fly ash and 5% boron carbide). The sample-7 of Al–Mg–Si-T6 alloy with 5% fly ash and 5% boron carbide possessed highest compression strength of 216.79 N/mm^2 which was 22% higher than the compression strength of the unreinforced Al–Mg–Si-T6 alloy. It was also observed that the compression strength decreases when the combination of 5% of fly ash and 7.5% of boron carbide exceeds 10% of reinforcement particles which was decreased by 12.5%. Even though the compression strength of the hybrid composite of Al–Mg–Si-T6 alloy with 5% fly ash and 7.5% boron carbide decreased slightly but it was still 23.2% higher than the unreinforced Al–Mg–Si-T6 alloy.

3.6. *Hardness test*

Hardness for the casted samples was calculated in terms of Rockwell B scale number (Fig. 11). The indenter used was 1/16″ steel ball. Form the results of the hardness test, it was observed that the hardness value increases with the increases in the percentage of the fly ash reinforcement (up to 15%). Among the cast samples reinforced with fly ash, the sample-2 of Al–Mg–Si-T6 alloy with 5% fly ash possessed improved hardness of 57.5 Rockwell numbers which was 3% higher than that of the unreinforced Al–Mg–Si-T6 alloy. The maximum Rockwell hardness number of 60.8 was recorded in the 15% reinforcement of fly ash particles which was 9% higher than the unreinforced Al–Mg–Si-T6 alloy. Even though there was a high harness in the 15% reinforcement of fly ash particles, the fluctuation of hardness values was observed which proves the presence of non-uniform distribution of the particles. From the result of addition of 20% of fly ash reinforcement particle in the Al matrix, it was confirmed that if the reinforcement percentage exceeds 15% then there will a drop in the mechanical properties of the composites. This was mainly due to the more quantity of reinforcement particles which lead to the particle clustering and the agglomeration of particles and it consecutively results in decrease in the harness value. This was also proved by Bandil et al. [54]. The hardness value for

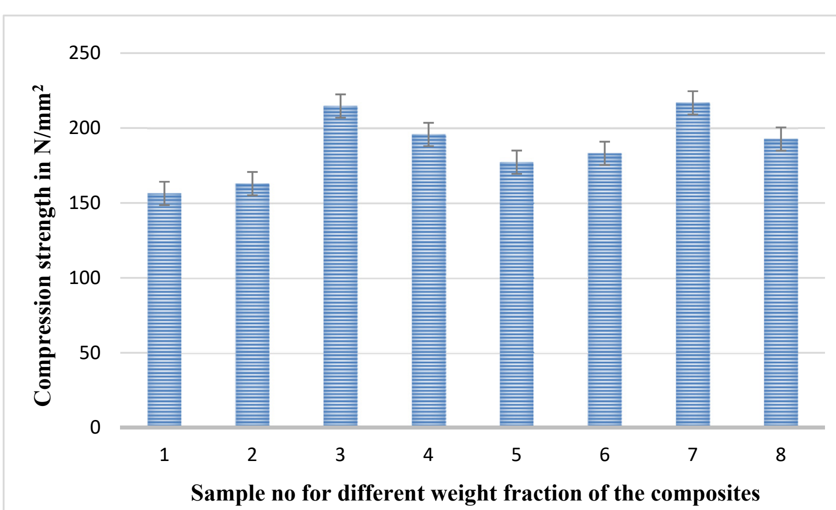

Fig. 10 – Compression strength vs different weight fraction of the composites.

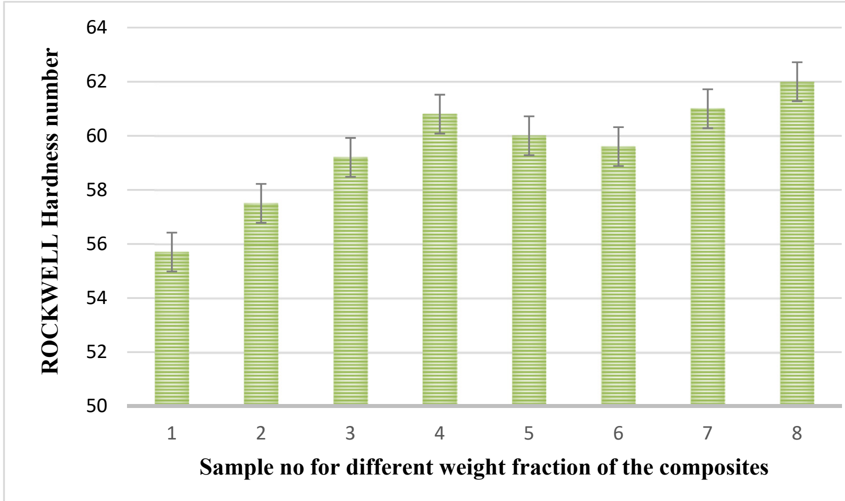

Fig. 11 – Hardness vs different weight fraction of the composites.

the 20% of the fly ash was decreased by 1.3% when compared with 15% of fly ash reinforcement. At the 20% reinforcement of the fly ash, the higher hardness value was obtained in the place where the fly ash was accumulated more and lower hardness values were obtained where there was an absence of reinforcement particles [55]. So, from the average harness value of 20% reinforcement of the fly ash was lower than the 15% reinforcement of the fly ash. In the case of hybrid composites, the maximum Rockwell hardness number of 62 was recorded for the reinforcement combination of 5% fly ash and 7.5% boron carbide which was 9.5% higher than the unreinforced Al–Mg–Si-T6 alloy. It was evident that the presence of boron carbide influences the hardness value because the presence of boron carbide increases the resistance towards the indentation and the penetration effect. So, the hardness value increases with the increase in the percentage of boron carbide.

3.7. *Density comparison*

Among the cast samples reinforced with fly ash, the sample-5 of AA6061 with 20% fly ash possessed lowest density of 2.631 g/cc which was 2.5% lower than that of the unreinforced Al–Mg–Si-T6 alloy. Increase in reinforcement percentage of fly ash, decreased the density of the composite (Fig. 12) [56]. Ahamad et al. explored that the main reason for the decrease in density of the composite was due to the evaporation of the water content while processing [57]. The decrease in composite density was due to the addition of fly ash reinforcement particles from sample 1-0% to sample 5–20% which shows good agreement with Ahamad et al. In the case of hybrid composites, another set of decrease of density was observed which was due to the addition of fly ash with boron carbide from sample 6- (5% + 2.5%) to sample 8-(5% + 7.5%). This gradual decrease was mainly due to the increase in the

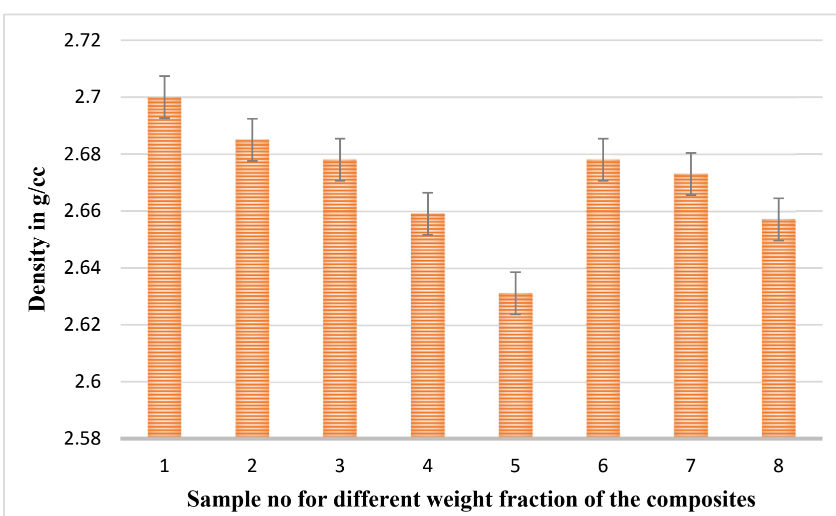

Fig. 12 – Density vs different weight fraction of the composites.

ceramic particle percentage. The sample-6 of Al–Mg–Si-T6 with 5% fly ash and 2.5% boron carbide possessed lowest density of 2.678 g/cc which was 0.81% lower than that of the unreinforced Al–Mg–Si-T6. From the results, it was clear that increase in reinforcement percentage, decreases the density of the hybrid composite.

4. Conclusions

The incorporation of fly ash and B_4C reinforcement particles in the Al–Mg–Si-T6 alloy has a positive effect on the mechanical properties. The presence of optimal combination in the composite: 5% B_4C with 5% fly ash in the Al–Mg–Si-T6 alloy enhances the overall strength of the composites. The following conclusions were drawn during the evaluation.

- From the results of optical microscope, SEM and EDS analysis, it was evident that the hybrid metal matrix composites with 5% fly ash and 5% B_4C reinforcement particles shows very less agglomeration and little clustering of particles at the grain boundaries. A perfect interfacial bonding with less voids which influences the enhancement of mechanical properties was noted too.
- When the percentage reinforcement particles exceeded the optimal combination of 10%, there was found high chance of agglomeration and clustering of the reinforcement particles which in turn seems to affect the mechanical properties of the composites.
- The maximum tensile strength of 184.72 N/mm^2 was observed in the optimal combination of 5% fly ash and 5% boron carbide. This was 3.4% higher than of composite made by using 10% reinforcement of fly ash and 18.7% higher than the unreinforced Al–Mg–Si-T6 alloy. This was due to the perfect interfacial bonding with less clustering of reinforcement particles.
- The incorporation of 7.5% of boron carbide with 5% of fly ash in Al–Mg–Si-T6 alloy triggered an enhancement on hardness of 61 Rockwell hardness number which was higher than the 15% of fly ash reinforcement particles and also 11.3% higher than the unreinforced Al–Mg–Si-T6 alloy. Even though the presence of reinforcement particles increases the hardness values, the hardness value decreases with the incorporation of 20% of fly ash. This was due to the agglomeration and clustering of the particles.
- The sample-7 of Al–Mg–Si-T6 alloy with 5% fly ash and 5% boron carbide possessed highest compression strength of 216.79 N/mm^2 and it was 38.6% higher than the compression strength of the unreinforced Al–Mg–Si-T6 alloy. The sample-5 of Al–Mg–Si-T6 with 20% fly ash possessed the lowest density of 2.631 g/cc and it was 2.5% lower than the density of the unreinforced Al–Mg–Si-T6 alloy.
- The results obtained from the mechanical characterization represented by the addition of optimal combination of fly ash and boron carbide up to 10% (5% + 5%), the properties such as tensile strength, compression strength and hardness increased when compared with the other combination and the unreinforced Al–Mg–Si-T6 alloy. But beyond 10%, the properties started decreasing; this was eventually due to the agglomeration and clustering of reinforcement particles. This decrease in strength can be attributed to the improper grain formation which was revealed in the microstructure study. Finally, the proposed aluminium (Al–Mg–Si-T6) hybrid metal matrix composite with the optimal combination of fly ash and boron carbide up to 10% (5% + 5%) can be adopted for the fabrication of drive shaft in race cars.

Author contributions

M. Saravana Kumar – Conceptualization, methodology, investigation, Writing - Original Draft, Writing - Review & Editing. M. Vasumathi: Supervision, S. Rashia Begum: Project administration, Scutaru Maria Luminita- Writing - Review & Editing, Sorin Vlase- Writing - Review & Editing, C.I. Pruncu – Interpretation, Writing - Review & Editing.

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Declaration of Competing Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.

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