Fabrication and tribological response of aluminium 6061 hybrid composite reinforced with bamboo char and boron carbide micro-fillers

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Abstract. Metal matrix composites (MMCs) have a wide scope of industrial applications and triumph over conventional materials due to their light weight, higher specific strength, good wear resistance and lower coefficient of thermal expansion. The present study aims at establishing the feasibility of using Bamboo charcoal particulate and boron carbide as reinforcements in Al-6061 alloy matrix and to investigate their effect on the wear of composites taking into consideration the interfacial adhesion of the reinforcements in the alloy. Al-6061 alloy was chosen as a base metallic alloy matrix. Sun-dried bamboo canes were used for charcoal preparation with the aid of a muffle furnace. The carbon content in the charcoal samples was determined by EDS (energy dispersive spectroscopy). In present study, stir casting technique was used to prepare the samples with 1%, 2%, and 3% weight of bamboo charcoal and boron carbide with Al-6061. The fabricated composites were homogenised at 570ºC for 6 hours and cooled at room temperature. Wear studies were carried out on the specimens with different speed and loads. It was found that wear rate and coefficient of friction decreased with increase in the reinforcement content.

1. Introduction

In early 1940s, the defense applications demanded a material with high strength and light weight for better portability[1]. The polymer industries flourished as work was done to improve the strength of plastic materials like glass fibers[2]. Of late, due focus has been given to Metal Matrix Composites (MMCs). The MMCs offered improved mechanical properties such as high tensile strength, high wear resistance, low coefficient of thermal expansion[3]. Aluminum is the most preferred base metal for the matrix of its light weight. The Al-MMCs shows better mechanical properties such as high stiffness to density ratio, better elevated temperature and improved wear resistance[4]. By virtue of this properties, it is widely used in different fields such as aerospace, automobile and marine industries[5]. B_4C is an ideal reinforcement for aluminum as it has high stiffness value of 445GPa and hardness of 3700HV. In the current work, bamboo char and boron carbide are used as reinforcements in Al6061 matrix to fabricate three different compositions of hybrid composites. The effect of these reinforcements on the tribological properties, response to different load and speed conditions has been studied in detail.

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2. Materials and Methods

The experimentation involved fabrication of Al6061 hybrid composites reinforced with varying weight fractions of bamboo char and boron carbide particulates (through stir casting), mechanical and tribological characterization of the as-cast composites. Al 6061 alloy was used as a matrix material whose chemical composition [in wt. %] has been listed in Table 1[6]. The alloying elements silicon and magnesium leads to high strength and hardness of the material. Al6061 being easily cast-able, preheating was not required before casting process or testing. The composition of aluminium 6061 is shown in Table 1. [7]. Bamboo charcoal has an enormous surface area to mass ratio and the ability to attract and hold (adsorption) a wide range of chemicals, minerals, radio waves and other harmful substances. 1 gram of bamboo has up to 600 square meters of surface area. Char is a light, black, porous material resembling coal, composed of about 80 % carbon. Good-quality char with the following characteristics can be produced from bamboo as shown in Table 2[8]. Charcoal made from bamboo has good properties, similar to wood and other ligno-cellulosic material in terms of high carbon content and calorific value. The Calorific value of bamboo charcoal is 6,900–7,000 kcal/kg. Boron carbide is known as robust ceramic material having high hardness compared to most of the materials. Boron carbide when used as a reinforcement helps increase the hardness of the composites and tends to counter the softness induced by bamboo char. It is insoluble in water with a melting point of 2763°C[9].

Table 1. Composition of Aluminium 6061[6][7]

Chemical Composition	Si	Mg	Cu	Cr	Fe	Ti	Zn	Mn	Al
%	0.4-0.8	0.8-1.2	0.15-0.4	0.04-0.35	0.70 Max	0.15 Max	0.25 Max	0.15 Max	Balance

Table 2. Composition of Bamboo Charcoal [8]

Composition	Carbon	Ash	Moisture	Others
%	80-85%	4.5- 6.5%	6-9%	2-3%

2.1 Preparation of reinforcement phases

To prepare charcoal from bamboo, fully grown stems (over 5 years old) were utilized. The stems were severed into uniform pieces of 20 cm x 5 cm x 5 cm. The samples were segregated as two types- wet and dry in initial stage. The dry samples were produced by keeping the pieces under the sun light for 7 days. The wet samples were directly used without drying after cutting [10]. Amba Chaithanyasai et al used powdered egg shell as reinforcement due to enriched carbon content[11]. Viney Kumara et al used magnesium with fly ash particulates to good effect [12]. K Rajkumar et al studied the mechanical properties of Al (6061) & B_4C composite for cleaner energy like microwave heat treatment for 5%, 10%, 15% weight composition of B_4C [13]. In this study bamboo charcoal is used as it has rich in carbon content along with boron carbide (Reinforcement size~60μm).

The bamboo stems were successively wrapped with aluminium foil to prevent any ingress of air and moisture into the wrapping. Tiny holes were created on the outer layers of the foil wrapping to avoid the bursting when the trapped air gets expanded by heat. Initially, the tiny white pores exhumed white smoke which turned into yellow after 15 minutes of continuous heating at a temperature of 700°C. This yellowish colour was attributed to liberation of bamboo tar during heating. The process was deemed to be complete when the yellow vapours were completely released. The process produced unpleasant smell. After cooling, the wrapped samples were taken out and charred bamboo specimens were crushed to make powder. To analyse the carbon composition, energy dispersive spectroscopy was carried out. Scanning electron microscope used for EDS analysis of the bamboo char particles[14]. One sample which had the output of highest fixed carbon (charring duration~15 minutes) was taken up for EDS analysis[12]. The carbon content was found to be 43.23% of weight for 15 min dry sample after the EDS analysis and Table 3 shows the composition of different elements in bamboo char.

Table 3. Result of elemental analysis on EDS.

Element	Carbon	Oxygen	Aluminum	Silicon	Potassium
Weight (%)	43.23	35.06	0.31	17.58	3.82
Atomic (%)	55.15	33.59	0.18	9.59	1.50

2.2 Stir casting of Al 6061 reinforced with Bamboo charcoal- Boron Carbide particles

Commercially available Aluminium 6061 bars (2 in. diameter) were cut into smaller pieces and placed in a crucible, allowed to melt at 800^0C[15]. After achieving molten state, degasification was conducted employing carrier Nitrogen gas [14]. The reinforcements (before adding into the melt) and the moulds were preheated in a separate furnace at 550^0C for 2 hours to avoid shrinkage defects during casting [16]. The Mechanical stirrer mechanism was fastened at the top of the furnace. The stirrer was used to create a vortex in the melt into which the reinforcements were added periodically to prevent heat loss and a consequent drop in furnace temperature.

Table 4. Details of the different composites fabricated using bamboo char and boron carbide

Composition designation	Bamboo char (wt.%)	Boron carbide (wt.%)	Al6061 (wt.%)
S-I	1	1	98
S-II	2	2	96
S-III	3	3	94

On completion of the stirring and addition of reinforcements, the furnace was allowed to heat to 800^0C for one hour, after which the mixture melt was poured into the preheated permanent moulds and allowed to solidify for 12 hours[17]. The as-cast specimens were then subjected to homogenization at 560^0C for 10 hours and normal cooling outside the furnace for uniform grain size within the composites. Three compositions were fabricated, details have been shown in Table 4. Figure 1 shows the optical micrographs of the fabricated composites revealing the distribution of the bamboo char and boron carbide particulates within the bright Al6061 matrix. As the weight content of the reinforcement increases, the bright phase of Al-6061 is found to diminish. There were no clusters of reinforcements or micro-cracks observed in the as-cast compositions which could be attributed to the pre-heating of the reinforcement before addition into the molten alloy during stir casting. The presence of Magnesium in Al6061 aided in the wetting of the reinforcements which improved the interfacial bonding between the matrix and the reinforcements. The reinforcement size of 60 µm ensured that porosity of the composites would remain minimal after solidification. The Rockwell B hardness number (100 kgf force with ball indenter) of the different compositions along with the density were measured to study the effect of the increasing weight content of the reinforcements on the hybrid Al6061 composites.

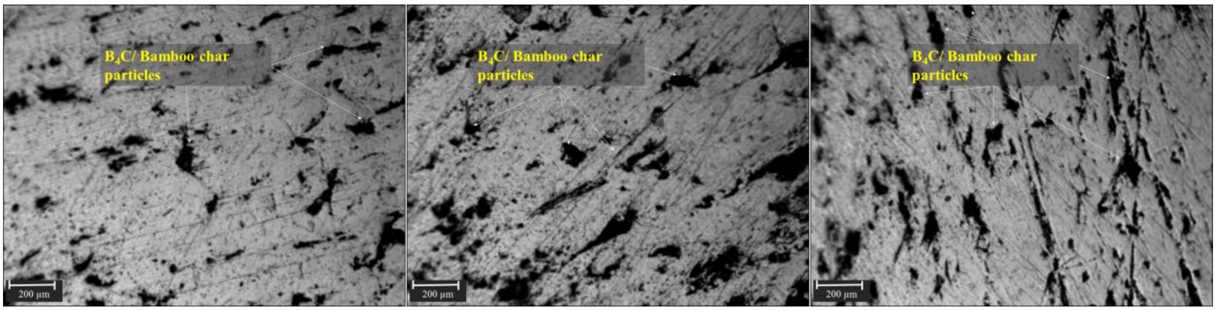

Figure 1. Optical micrographs of the fabricated composites (a) S-I (b) S-II (c) S-III

3. Tribological studies

The tribological studies of the composites were conducted through pin-on-disk wear tests as per ASTM G-99 standard on a standard wear tester, DUCOM TR-201 CL[7]. Three speeds of 400 RPM, 500 RPM and 600 RPM were chosen while normal load applied during the wear test were 9.8 N. 19.6 N and 29.4 N respectively[18]. A total of 27 wear test trials were conducted for different loads and speeds for a running distance of 500 m each. The specific wear rate and the friction coefficients were noted during each run.
The specific wear rate '$\dot{W}$' was computed by the weight loss method as given by Eq. (1), in which 'ΔW' is weight loss, 'F' is the normal load on the specimen and 's' is the running distance for the wear test. [14]

$$\dot{W} = \frac{\Delta W}{Fs} \tag{1}$$

4. Results and Discussion

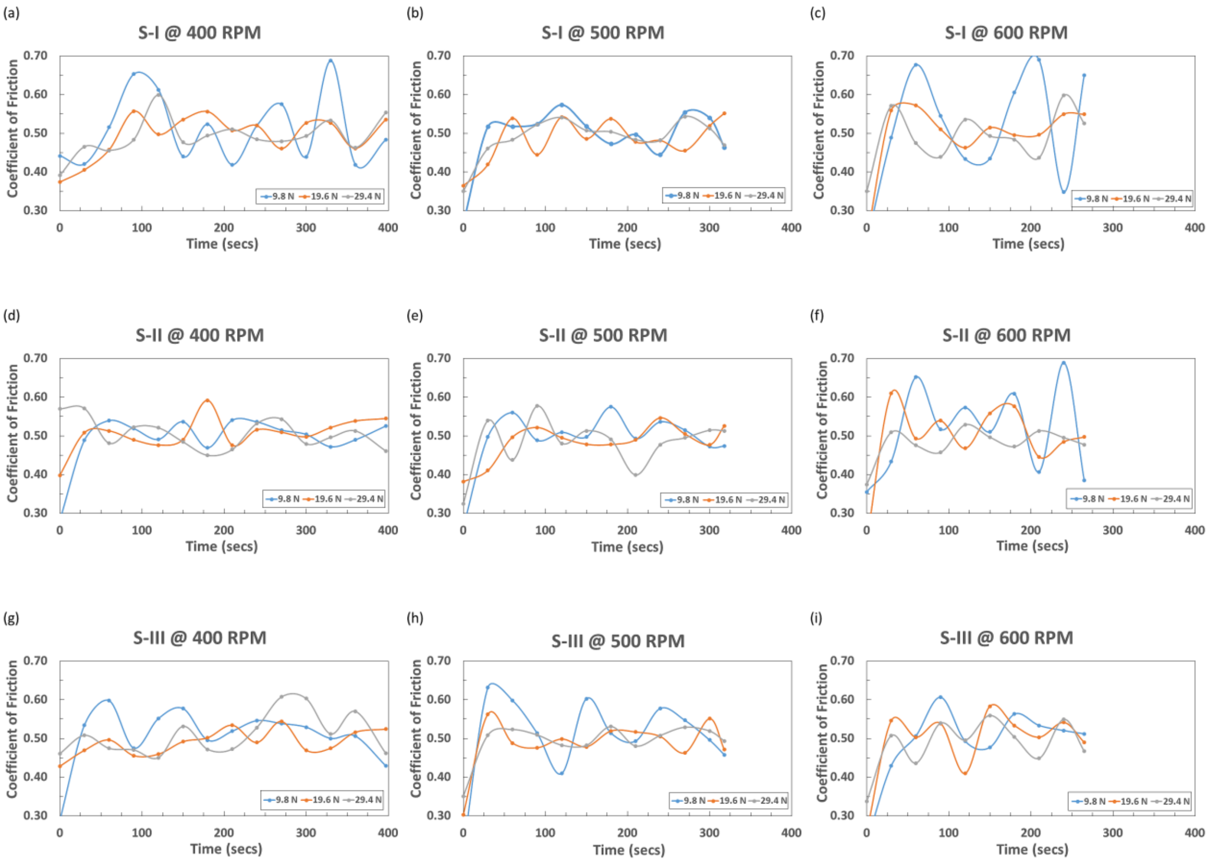

Figure 2. Variation of friction coefficients at different speeds and loads

The variation of the coefficient of friction for the different speeds and normal loads are shown in Figure 2. For the composition, S-I, the peak coefficient of friction was found to have registered at lower load of 9.6 N. But there was significant fluctuation in the coefficient of friction with time at this load and this tendency was repetitive over higher speeds of 500 RPM and 600 RPM. Since S-I contained low content of reinforcements, the tribological behavior reflected more or less that of the base alloy Al6061. As the weight content of the reinforcements increased, the coefficients of friction got stabilized at 400 RPM and 500 RPM as observed for S-II and S-III compositions. Nevertheless, at the high speed of 600 RPM, the widest fluctuation in the coefficients of friction was observed for S-I and S-II compositions. This could be due to the lower bamboo char content in S-I and S-II. Bamboo

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char being majorly carbon and of a frangible nature, its behavior would be similar to graphite which is a very popular dry lubricant. The compositions with lower bamboo char content would also release bamboo char at a lower rate due to which the coefficient of friction was found to rise and fall steeply. However for the composition S-III, along with a higher content of bamboo char, boron carbide was also available in higher quantity. Boron carbide being an abrasive reinforcement can get entangled between the wear surfaces and give rise to a three-body abrasive phenomena. Those boron carbide particles which do not take part in the formation of the primary plateau would cause abrasion at the interface causing a rise in the coefficient of friction. At higher speeds, the sliding is faster along with the release of the boron carbide particles[15-16]. Figure 3 shows the variation of the average coefficient for friction for the three compositions. All the three compositions showed minimal variation in the average coefficient of friction at different loads and speeds. S-III composition showed the most stable coefficient of friction among all three compositions.

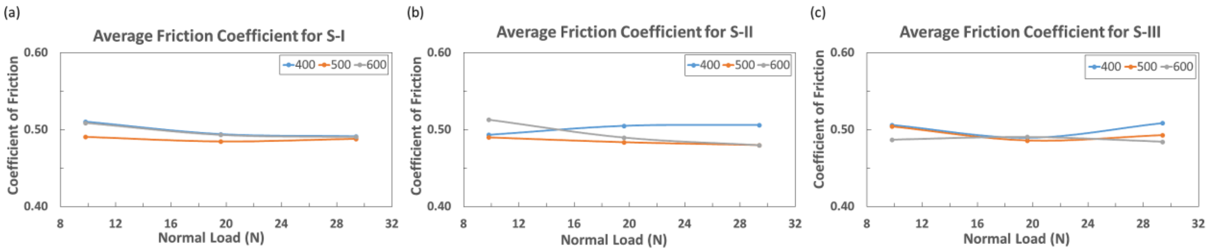

Figure 3. Variation of average coefficient of friction for different compositions

The effect of different speeds and loads on the wear rate of the three compositions has been shown in Figure 4. S-I composition showed a reduction in wear rate with increase in loads at 400 and 600 RPM, while at 500 RPM, the wear rate was found to increase for 19.6 N and then again reduced for 29.4 N. S-II and S-III showed a steady decline in the specific wear rate as normal load and sliding speed were increased. With the increase in the content of the bamboo char and boron carbide, the specific wear rate was found to decrease for all three compositions (Figure 4(d)). The reason for reduction in wear rate could be attributed to two phenomena- bamboo char behaving like a frangible, dry lubricant that not only stabilized the coefficient of friction but also helped in reducing the rate of wear and boron carbide being a hard ceramic improved the hardness of the composite and prevented surface deterioration thus improving the wear resistance of the composites.

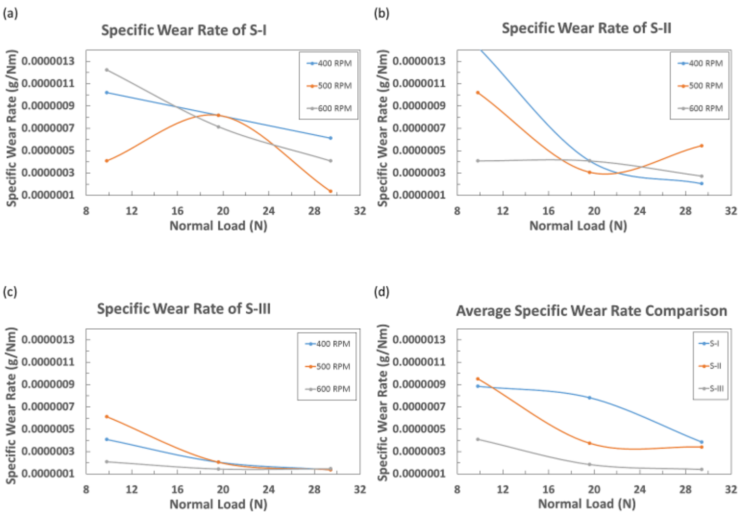

Figure 4. Variation of specific wear rate for different compositions (a) S-I (b) S-II (c) S-III (d) Average specific wear rate for all compositions

To understand the wear sequence on the surface of the composites, wear surface morphology through optical microscopy was taken up. Figure 5 shows the wear morphology studies on the three compositions. The wear micrographs of S-I composition showed that at 400 RPM, uniform wear takes place, but as the speed is increased to 500 RPM, there were few wear grooves present on the surface indicating scoring by free boron carbide particles. At 600 RPM, formation of primary plateau was seen which resisted further wear. During a two-body wear interaction as existing in the wear studies taken up, the contact peak asperities on the softer surface, in this case, the composite specimen undergo plastic deformation. On exceeding a critical deformation beyond the breaking point, the asperities get separated from the parent specimen and in turn get pulled towards the direction of the sliding. Subsequent removal of such wear debris led to formation of cracks or grooves and continued heavy wear would lead to formation of craters. But when the parent alloy contains foreign particles like reinforcements, removal of parent alloy material also releases the reinforcement particles that get mixed along with the wear debris of the alloy and this mechanically mixed layer gets redistributed as primary plateau on the specimen surface. S-II showed groove formation at 400 RPM itself and faster formation of the primary plateau at 500 RPM itself. Thus, the minimal difference in wear rate at 500 RPM and 600 RPM could be due to this phenomenon. The formation of primary plateau was found to be the fastest in S-III composition where at 400 RPM itself, isolated plateau could be seen. Thus, the average wear rate for S-III was found to be lowest among all three compositions and it could be summarized that as the percentage of bamboo char and boron carbide increased, the formation of primary plateau gets accelerated. This non-peeling, mechanically mixed layer resists wear and improves wear resistance. [19]

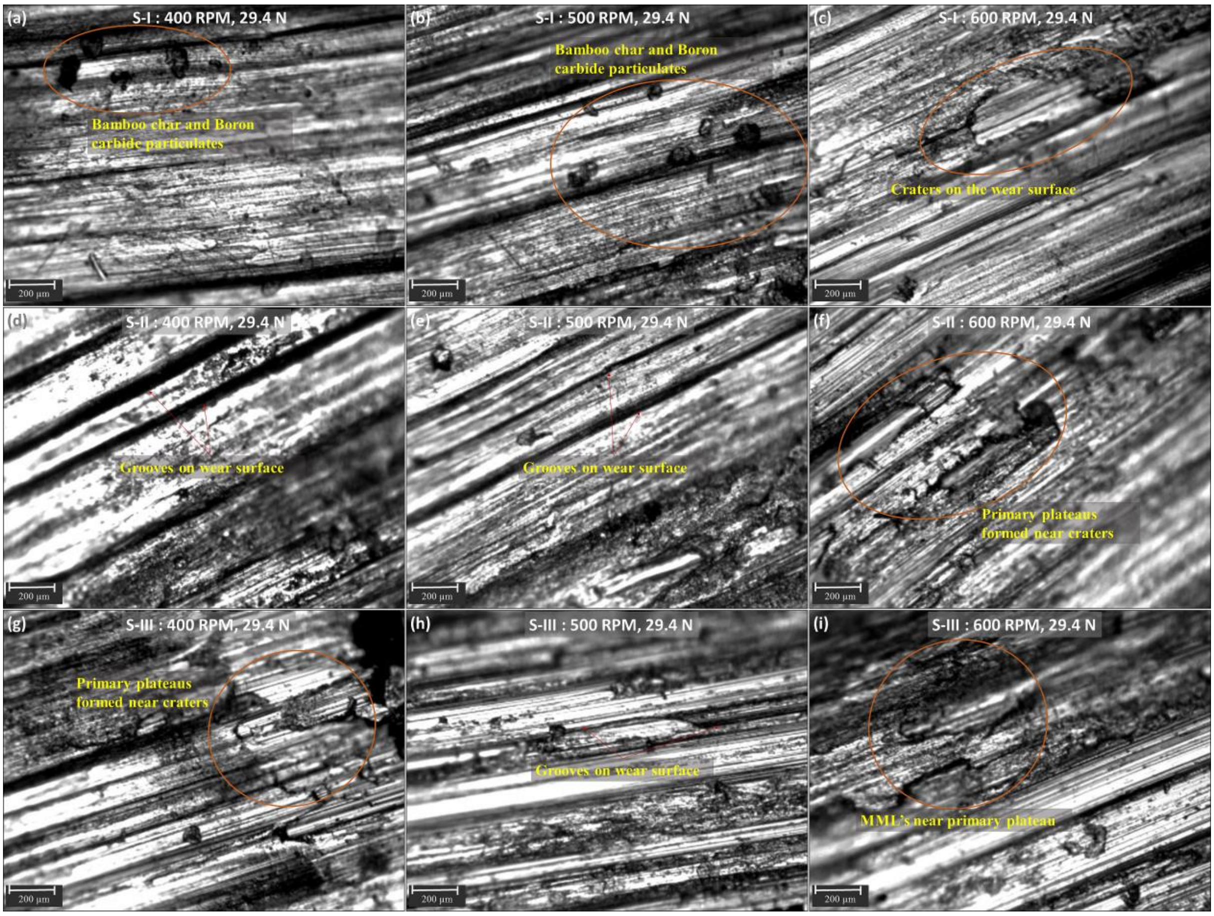

Figure 5. Wear Surface morphology for the different compositions

Mechanical characterization of the fabricated Al6061 hybrid composites were taken up to study the response due to addition of bamboo char and boron carbide reinforcements. The Rockwell B hardness values of the different compositions is shown in Figure 6 (a). On increasing the weight fraction of the reinforcement, the hardness of the composites is found to increase. The bamboo char being softer would reduce the hardness if added alone, but presence of harder boron carbide particles led to increase in the hardness. The mass density is found to decrease on increasing the weight fraction of the reinforcements (Figure 6 (b)). The decrease in the density could be due to the lower density of bamboo char as well as boron carbide reinforcements [17].

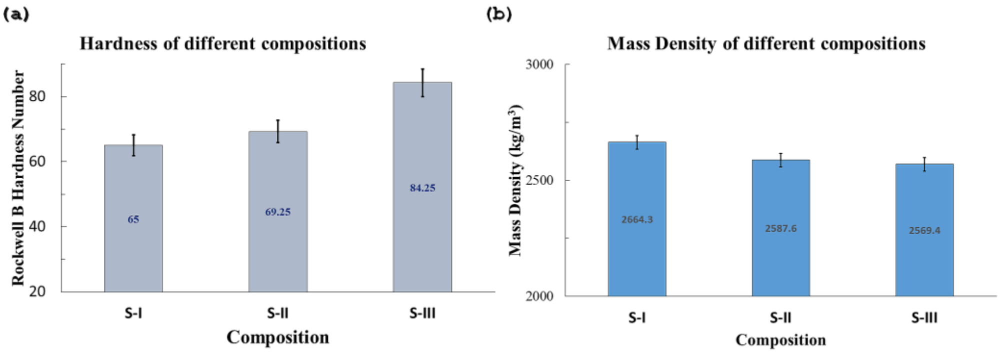

Figure 6. Effect of reinforcement content on (a) Hardness (b) Mass Density

5. Conclusions

The fabrication of three different compositions of Al6061 hybrid composites reinforced with bamboo char and boron carbide micro-fillers was completed and the tribological analysis yielded the following conclusions. As the weight fraction of the bamboo char and boron carbide was increased, the average coefficient of friction was found to have stabilized over longer sliding duration. The wear resistance of the Al6061 hybrid composites increased on increasing the weight fraction of bamboo char and boron carbide which was attributed to the acceleration in the formation of primary plateau’s consisting of mechanically mixed and a non-peeling layer. Hence Bamboo char along with Boron carbide as micro fillers can be effectively used to impart wear resistance to Al6061 alloy. Also bamboo char synthesized from naturally sourced bamboo offers an economical alternative for a dry lubricant.

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