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Influence of rare earth addition on the properties of AA6351 hybrid composites

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ABSTRACT

Nowadays, the effect of the rare earth addition on the performance of aluminium matrix composites is a major interest for many researchers. The present research work emphasis is on the study of the effect of praseodymium oxide (rare earth element) addition on the performance of AA6351 hybrid composites. Silicon carbide and rice husk ash in the weight proportions of 6:2 were ball-milled with various weight percentages (0.4%, 0.8%, and 1.2%) of praseodymium oxide to have a consistent microstructure and combined density equivalent to the AA6351 matrix alloy. Further, AA6351 hybrid composites with the ball-milled reinforcement of silicon carbide, rice husk ash, and praseodymium oxide were produced using stir-casting technique. Physical, microstructural, mechanical, and tribological characterization were done to study the impact of praseodymium oxide addition on the developed hybrid composites. An increment of 2.61% in the density, 49.40% in the microhardness, and 19.78% in the ultimate tensile strength was recorded with the incorporation of 1.2 weight percentage of praseodymium oxide in the AA6351 hybrid composites. The wear rate of the developed composites also improved by 32.92% with the addition of praseodymium oxide. The results exhibited a remarkable improvement in the performance of the AA6351 hybrid composites with the addition of rare earth element.

Keywords: Silicon carbide (SiC); Rice husk ash (RHA); Praseodymium oxide (Pr_6O_{11}); Ball-milling; Microstructure; Mechanical and Wear properties.

INTRODUCTION

Amongst the family of light weight metals, the aluminium metal matrix composites are most popular amongst the researchers. The superb mechanical and wear resistant properties along with the light weight have made aluminium matrix composites a suitable choice for the development of various products. The parts developed from the aluminium matrix composites have wide applications in the field of aeronautics, defence, automobile, and other engineering domains (Arora and Sharma 2017; Bodunrin et al. 2015). The development of monolithic aluminium composites took over the place of unreinforced alloy for various applications, but hybrid aluminum matrix composites have overcome the use of unreinforced alloy and monolithic aluminium matrix composites as they possess superior properties over them (Rajmohan et al. 2013; Krishna and Xavior 2014). The reduction of the overall cost of the reinforcement motivates many researchers to develop aluminium hybrid composites with a combination of industrial-agro wastes and synthetic reinforcements. This type of combination of reinforcements also helped in reducing the waste disposal cost and environmental pollution also (Singh and Chauhan 2016; Lancaster et al. 2013; Kanayo et al. 2013; Siva and Shoba 2014; Alaneme et al. 2014; Fatile et al. 2014). Literature (Sharma et al. 2015a; 2015b; Arora and Sharma 2017) has also shown that the ball-milling of the reinforcements is one of the novel techniques in producing the combined reinforcement with density comparable to the matrix alloy for the production of hybrid composites.

The results from literature also show that an enhancement in the wear and mechanical properties can be achieved with the addition of rare earth elements to the aluminium matrix composites. The effect of addition of yttrium oxide (Y_2O_3) on the mechanical, microstructure, and corrosive properties of Al/Y_2O_3 composites has been studied by Bouaeshi and Li (2007). An improvement in the microstructure along with the improved mechanical and wear properties with the addition of Y_2O_3 was reported during characterization of the developed composites. Moosa et al. (Moosa and Awad 2016) characterized the Aluminium rare earth alloy reinforced with rice husk ash and yttrium oxide (Al-Re/RHA/Y_2O_3) hybrid composites fabricated by two-step stir-casting method. Density and porosity measurement, hardness, and wear study of the fabricated composites by varying the weight percentage of RHA and Y_2O_3 were reported in this research work. The results showed a refinement in the microstructure with the increased content of Y_2O_3. The characterization results also exhibited the enhanced hardness and the wear resistance of the fabricated composites with the addition of Y_2O_3. Anilkumar et al. (2014) investigated the corrosion and wear behaviour of Aluminium 6061 reinforced with Beryl particles and cerium oxide (Al6061/Beryl/CeO_2) hybrid composites developed by stir-casting technique. The results exhibited an increment in the hardness and the tensile strength of the developed composites with the addition of 0.2% cerium oxide (CeO_2). The addition of CeO_2 also improved the wear and corrosion resistance of the fabricated composites.

A limited research work on the use of rare earth elements in aluminium matrix composites is available in the literature. So, an attempt has been made in the present research work to develop and characterize AA6351 hybrid composites using a combination of synthetic (silicon carbide, SiC), an agro waste (rice husk ash, RHA), and rare earth element (praseodymium oxide, Pr_6O_{11}) as reinforcement via stir-casting route. The prime endeavor of the present research work is to study the effect of addition of varying weight percentages of praseodymium oxide with SiC and RHA on the performance of the AA6351 hybrid composites. The fabricated composites were characterized in terms of density, porosity, microstructure, tensile strength, and wear behaviour by the authors.

RESEARCH METHODOLOGY

Ball-Milling of Reinforcements

In the previous research work done by the authors Arora and Sharma (2018a; 2020b), AA6351 mono- and hybrid composites were developed by stir-casting technique and characterized in terms of density, hardness, tensile strength, and wear resistance. The results exhibited that the performance of the AA6351 with 6 weight percentage of SiC and 2 weight percentage of RHA was the supreme as compared to the other developed hybrid composites. Keeping this fact in view, ball-milling of various weight percentages of SiC:RHA:Pr_6O_{11} in the proportions of 6:2:0.4, 6:2:0.8, and 6:2:1.2 was done to produce the combined reinforcement for the development of AA6351 hybrid composites. Ceramic balls of ϕ12 mm were used as the grinding medium with ball-to-powder ratio as 5:1 at 200 rpm. A horizontal type ball-mill was utilized for the ball-milling of the mixture, and the ball-milling was done from 0 hours to 150 hours with an increment of 15 hours at each step. Density calculation using Archimedes principle and microstructural characterization using scanning electron microscope (SEM) of the ball-milled powders at each distinct milling time was carried out for the density homogenization of the combined reinforcement.

Fabrication of Hybrid Composites

AA6351 hybrid composites with ball-milled reinforcement SiC, RHA, and Pr_6O_{11} were developed using stir-casting technique. The chemical composition of the AA6351 used for the present research work is represented in Table 1. Table 2 represents the designations of AA6351 hybrid composites with varying ratio of incorporated reinforcements.

Table 1. Chemical composition of AA6351 matrix alloy.

Element	Si	Mn	Mg	Cu	Fe	Cr	Zn	Al
Weight %	0.95	0.59	0.72	0.077	0.187	<0.025	<0.017	Balance

Table 2. AA6351 hybrid composites designations.

Composition ($SiC:RHA:Pr_6O_{11}$)	6:2:0.0	6:2:0.4	6:2:0.8	6:2:1.2
Designation	A11	A12	A13	A14

The ingots of AA6351 were charged in a crucible of graphite and heated up to 830°C ± 30°C temperature till all the metal was melted completely. A calculated amount of ball-milled reinforcement of SiC, RHA, and Pr_6O_{11} was preheated and introduced in the matrix melt for the fabrication of AA6351 hybrid composites. The melt was stirred at a speed of 400 rpm, and preheated reinforcement was incorporated to the matrix melt at this time. Even after the addition of complete reinforcement, the stirring was continued for another 10–12 minutes. The mixture was then allowed to be solidified naturally in the crucible only and collected for the development of characterization samples.

Characterization of Hybrid Composites

Porosity analysis was done by calculating the theoretical and experimental density of the cast composites. Microstructural study of the AA6351/SiC+RHA/Pr_6O_{11} hybrid composites was done with Zeiss EVO 18 machine scanning electron microscope (SEM). A standard process of metallography was used for producing the specimens, while etching of the specimens was done with the Kellar's etchant. Metatech (MVH-I) microhardness tester was used to evaluate the microhardness of the developed testing specimens at a load of 500g for 15s. The tensile testing was carried out as per ASTM B-557 standards using an Instron (100KN) UTM machine.

Adhesive wear test of the developed specimens was performed on the Ducom (TR-20LE) pin-on-disc machine in accordance with the ASTM G99 standards. The wear testing was done at the loads of 9.81N, 19.6N, and 29.41N, without use of any lubrication. A sliding speed of 1.5 m/s and a sliding distance of 2000 m were kept for all the experiments. Specific wear rate of the specimens was calculated using the following equation:

$$WR = \Delta V / F.L \quad (1)$$

where specific wear rate is represented by WR (mm^3/Nm), ΔV (mm^3) represents the loss of volume of the specimen after the wear test was performed, F (N) represents the value of applied load, and L (m) is denoting the value of sliding distance taken for all the investigations.

RESULTS AND DISCUSSION

Ball-Milling of Reinforcement

Density Measurement

The mismatch of the density of the incorporated reinforcements and the matrix alloy is one of the major causes of the agglomeration during the composite fabrication via stir-casting method. Density homogenization of the reinforcements SiC, RHA, and Pr_6O_{11} is done using ball-milling process to reduce the problem of agglomeration. The relation between the density of the combined reinforcement of SiC:RHA:Pr_6O_{11} as 6:2:0.4, 6:2:0.8, and 6:2:1.2 with the distinct milling times is shown in Figure 1. At 0 hours of milling time, the density of the ball-milled reinforcement (SiC:RHA:Pr_6O_{11} 6:2:0.4) was calculated as 3.08 g/cm^3. The value of density initially increased as 4.00 g/cm^3 up to 45 hours of milling time and further decreased with the increased milling time up to 120 hours. The density of the combined reinforcement became comparable to the density of AA6351 matrix as 2.67 g/cm^3 at the milling time of 105 hours as represented in Figure 1.

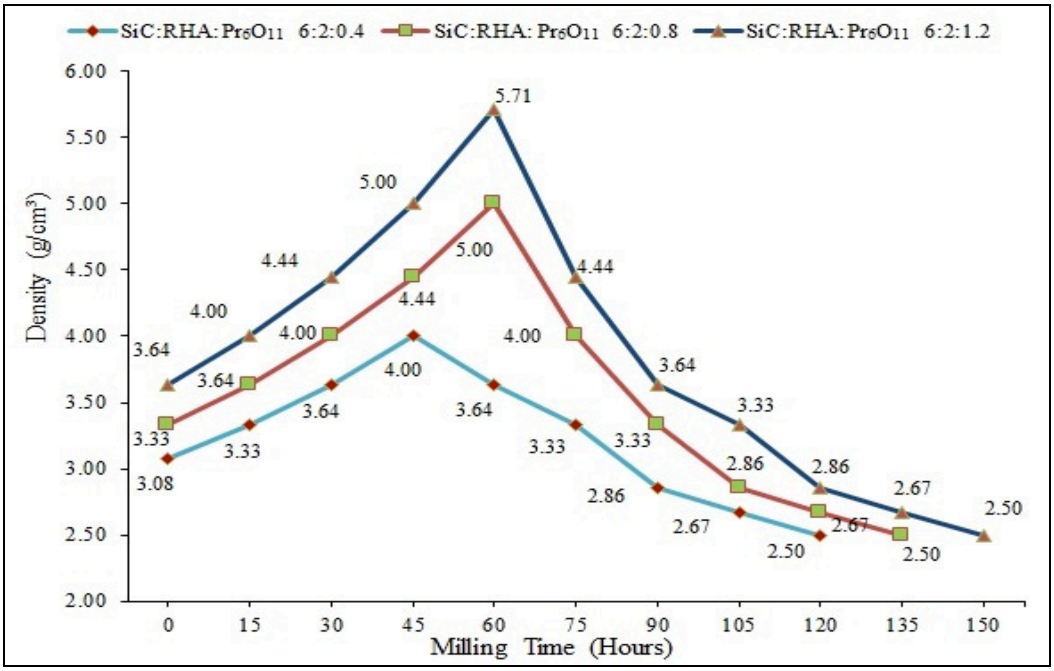


Figure 1. Variation of Density of Ball-milled Reinforcement (SiC:RHA:Pr_6O_{11} 6:2:0.4, 6:2:0.8, 6:2:1.2) as a Function of Milling time.

The density variation of the ball-milled reinforcement (SiC:RHA:Pr_6O_{11} 6:2:0.8) with the distinct milling time is also shown in Figure 1. The value of density increased from 3.33 g/cm^3 to 5.00 g/cm^3 from 0 hours to 60 hours milling time. With the further increase in milling time, the density value of the combined reinforcement continuously decreased up to 135 hours. The density value of the combined reinforcement became corresponding to the AA6351 alloy as 2.67 g/cm^3 at the milling time of 120 hours. The correlation between the value of density of the ball-milled reinforcement (SiC:RHA:Pr_6O_{11} 6:2:1.2) and the milling time is also represented in Figure 1. Initially, the density value of the combined reinforcement increased from 3.64 g/cm^3 to 5.71 g/cm^3 from 0 hours to 60 hours of milling time. With the further increase in milling time, the density value decreased and became proportionate to the AA6351 matrix alloy at the milling time of 135 hours.

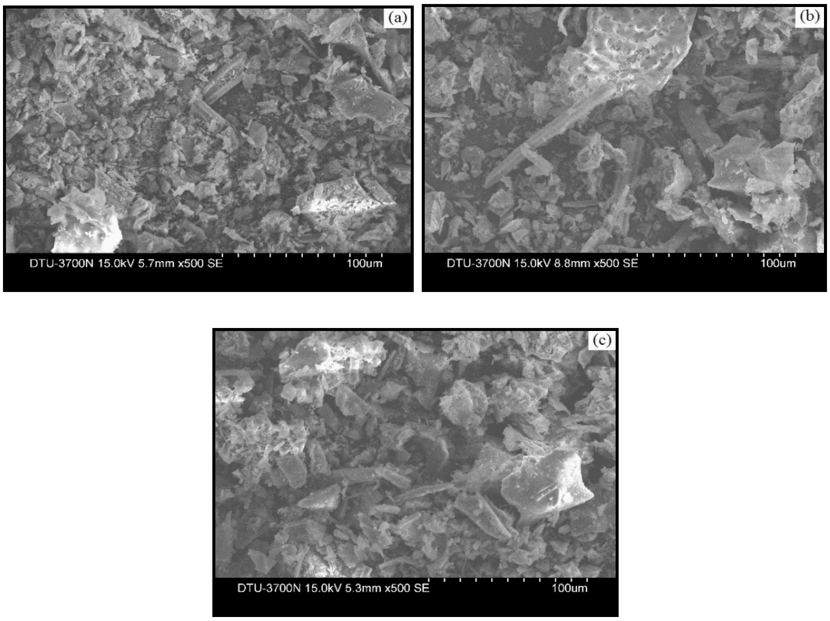
A similar trend of the initial increment of density of the combined reinforcement and then decrease in the density may be noticed in all the above three cases. This trend of increase of the density in all the above three cases was due to the increment of the Vander walls forces between the ingredients. The high energy collision of the grinding media with the reinforcements resulted in this enhancement of the Vander walls forces, decreased the intermolecular distance, and finally increased the value of the density. Because of this decrease in the intermolecular distance, the particles of combined reinforcement were closely bonded with each other, resulting in the increment of the density. With the further increase in milling time, an increase of temperature happened due to the combined effect of exothermic reactions and kinetic energy of the grinding medium (Suryanarayana 2001). With this increase of temperature, the Vander walls forces decreased, which resulted in the increment of intermolecular distances between the combined reinforcements and finally reduced the density. Similar results of decrease in the density of combined reinforcement with the increment of milling time have been reported by Sharma et al. (2015) also.

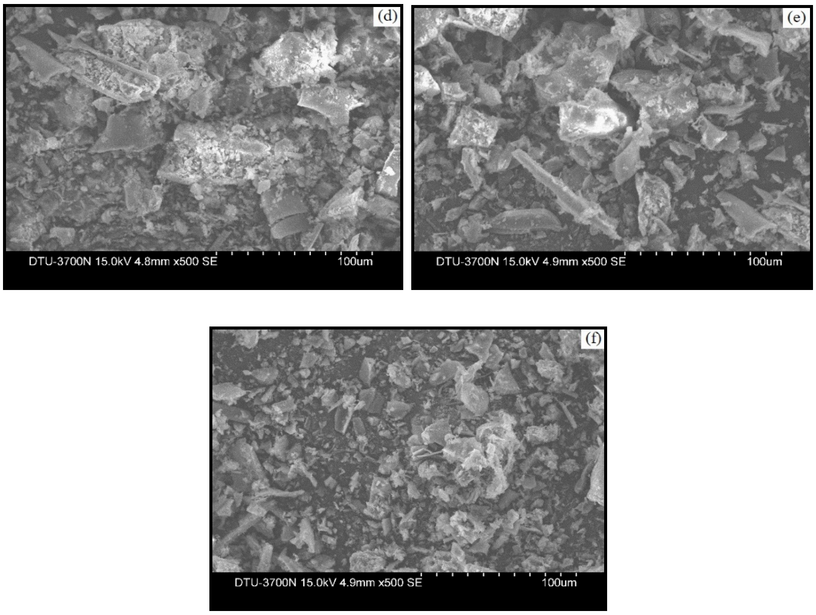
Microstructural Analysis

The SEM images were taken at the distinct milling times for analyzing the microstructure of the combined reinforcement. The SEM images of ball-milled reinforcement of SiC:RHA:Pr_6O_{11} as 6:2:0.4, 6:2:0.8, and 6:2:1.2 are represented in Figure 2 (a–h), Figure 3 (a–i), and Figure 4 (a–j), respectively. Figure 2 (a), Figure 3 (a), and Figure 4 (a) represent the SEM images at the milling time of 0 hours. The constituents, i.e., SiC, RHA, and Pr_6O_{11}, can be easily seen as the separate entities in these figures, since no ball-milling has been performed at this stage. The ball-milling process includes the regular crushing, cold-welding, fracturing, and rewelding of the combined reinforcement due to the impact of grinding media. At the milling time of 15 hours and 30 hours, fracturing of the constituents took place and becomes clearly visible in Figure 2 (b-c), Figure 3 (b-c), and Figure 4 (b-c), respectively. Because of the crushing phenomena between the ball-mill vial and the grinding media, this fracturing of the constituents took place during ball-milling process.

Further, as the milling time increased to the 45 hours, due to the plastic deformation, work hardening and fracturing of the constituents happened as presented in Figure 2 (d), Figure 3 (d), and Figure 4 (d), respectively. At the milling time of 60 hours, a phase of cold welding of the constituents was reached, due to which the reinforcement became overlarge, and a relative uniform microstructure may be seen in Figure 2 (e), Figure 3 (e), and Figure 4 (e), respectively. As the milling time further increased to 75 hours and 90 hours due to the further crushing of the constituents, more uniformity in the microstructure is visible in Figure 2 (f-g), Figure 3 (f-g), and Figure 4 (f-g), respectively. For the composition (SiC:RHA:Pr_6O_{11} 6:2:0.4), a nearly consistent microstructure is achieved at the milling time of 105 hours and is shown in Figure 2 (h), whereas more fine combined reinforcement with refined microstructure is visible in Figure 3 (h) and Figure 4 (h), respectively.

An appropriate mixing of the reinforcements with approximate uniform microstructure is observed for the composition (SiC:RHA:Pr_6O_{11} 6:2:0.8) at the milling time of 120 hours and presented in Figure 3 (i). At this milling time of 120 hours, a coarser surface morphology due to the additional crushing is observed in Figure 4 (i). With the further increase of milling time as 135 hours, a consistent microstructure for the composition (SiC:RHA:Pr_6O_{11} 6:2:1.2) is observed as shown in Figure 4 (j).





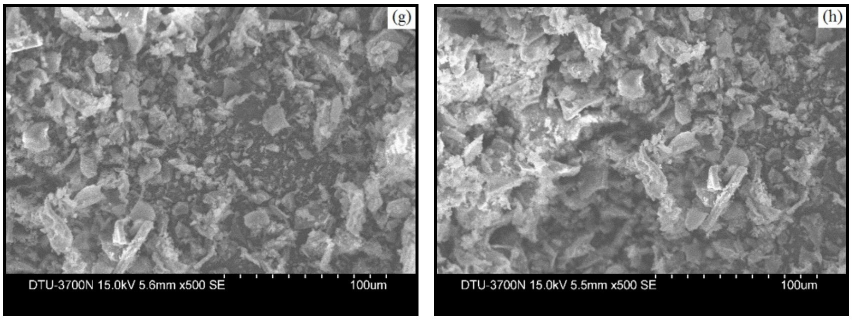
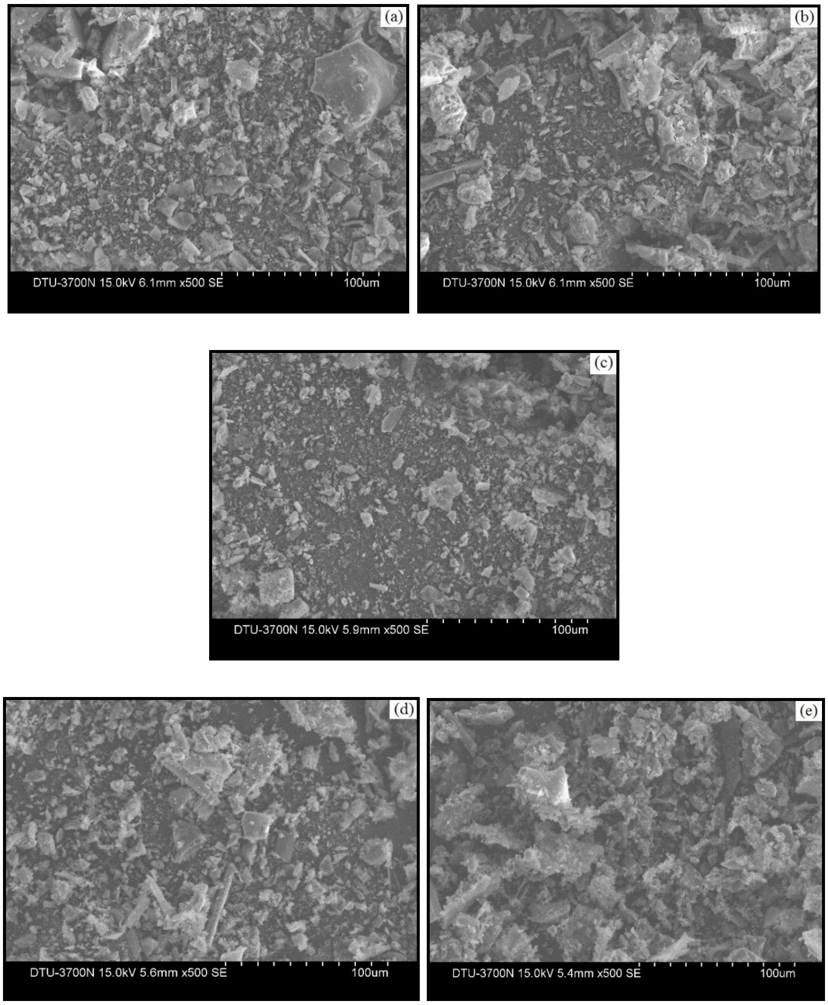


Figure 2. SEM images of Ball-milled Reinforcement (SiC:RHA:Pr_6O_{11} 6:2:0.4) at milling times a) 0 hours, (b) 15 hours, (c) 30 hours, (d) 45 hours, (e) 60 hours, (f) 75 hours, (g) 90 hours, (h) 105 hours.



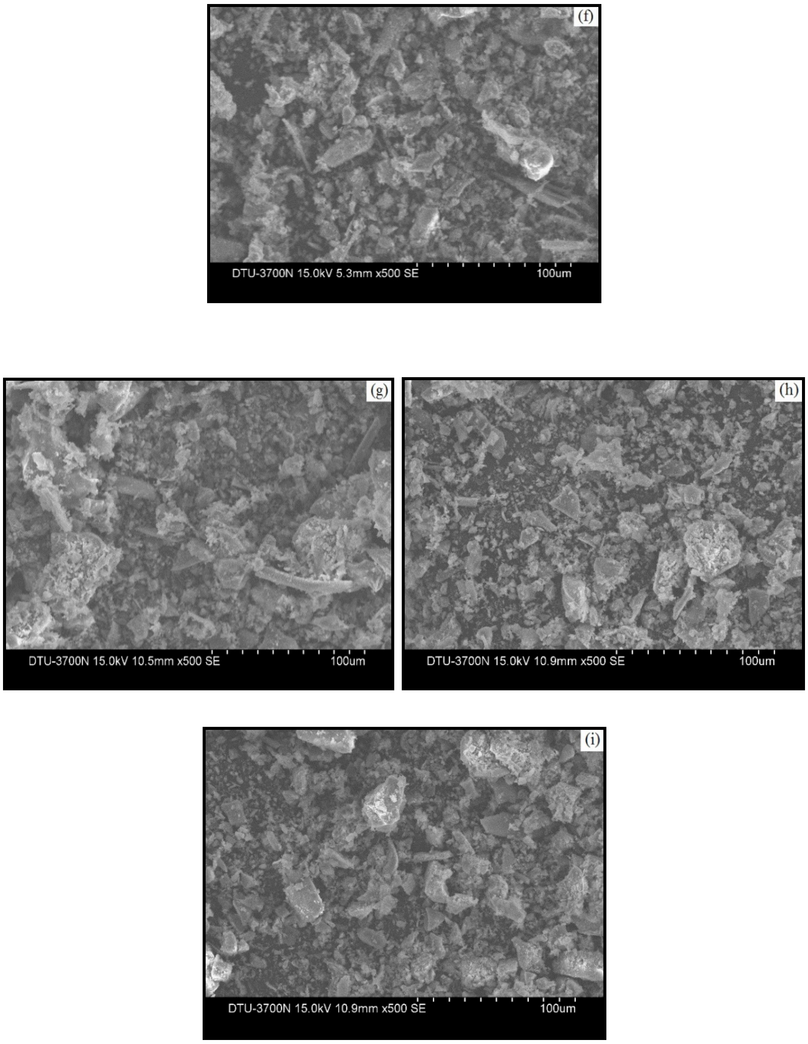
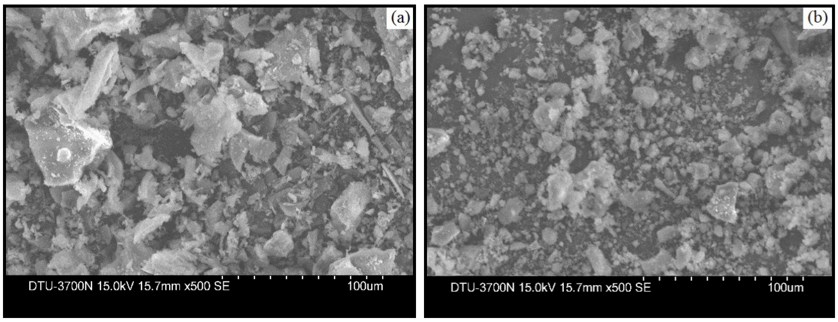
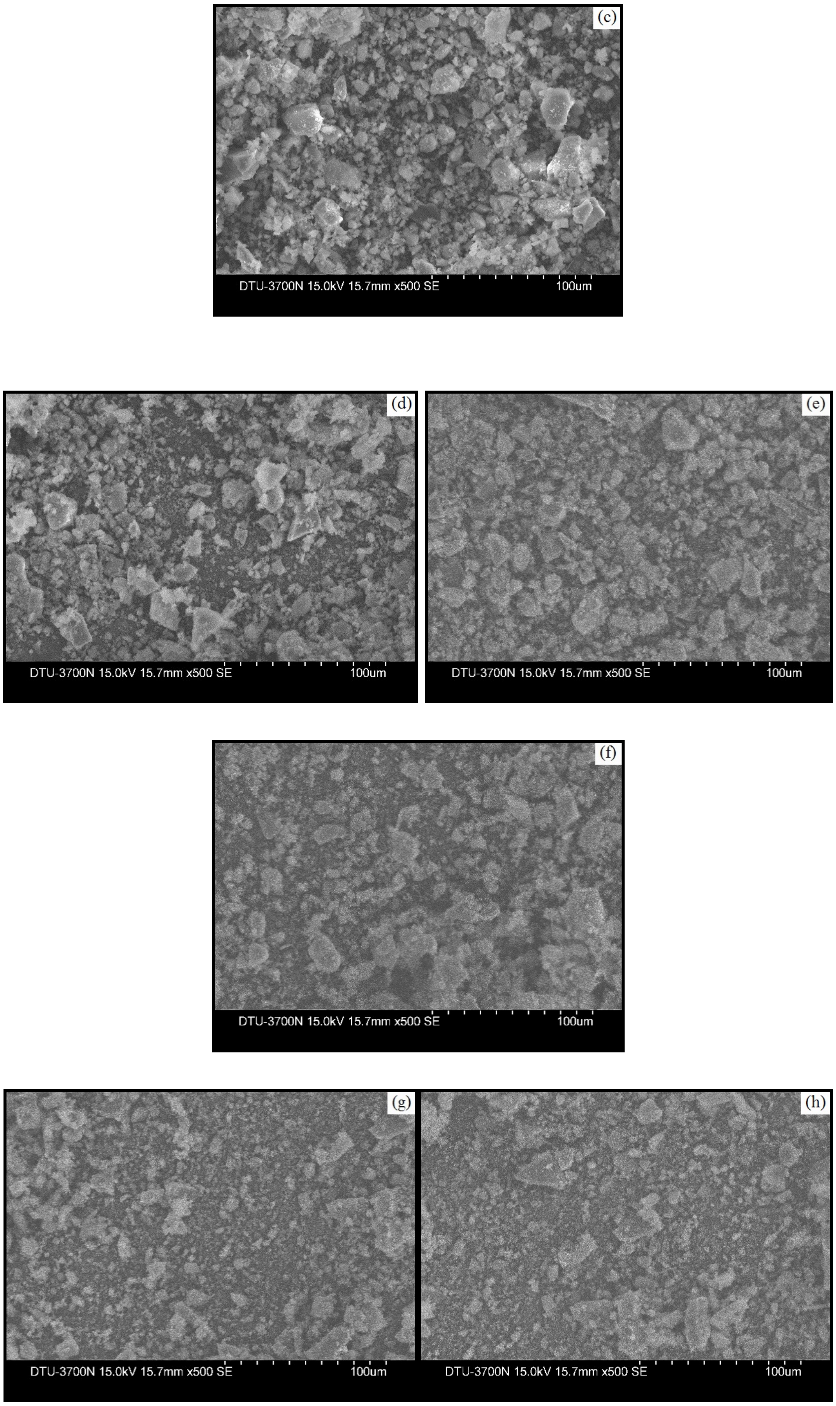


Figure 3. SEM images of Ball-milled Reinforcement (SiC:RHA:Pr_6O_{11} 6:2:0.8) at milling times 0 hours, (b) 15 hours, (c) 30 hours, (d) 45 hours, (e) 60 hours, (f) 75 hours, (g) 90 hours, (h) 105 hours, (i) 120 hours.




(c)
DTU-3700N 15.0kV 15.7mm x500 SE
100um
(d)
DTU-3700N 15.0kV 15.7mm x500 SE
100um
(e)
DTU-3700N 15.0kV 15.7mm x500 SE
100um
(f)
DTU-3700N 15.0kV 15.7mm x500 SE
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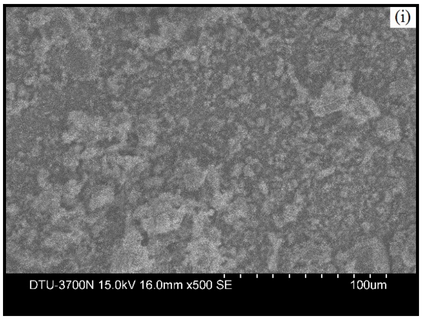
(g)
DTU-3700N 15.0kV 15.7mm x500 SE
100um
(h)
DTU-3700N 15.0kV 15.7mm x500 SE
100um



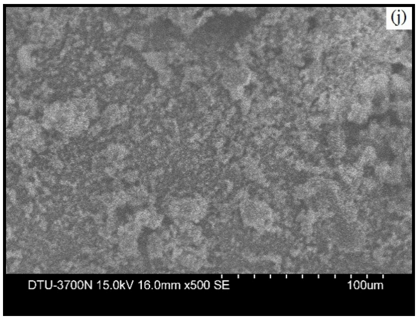


Figure 4. SEM images of Ball-milled Reinforcement (SiC:RHA:Pr_6O_{11} 6:2:1.2) at milling times (a) 0 hours, (b) 15 hours, (c) 30 hours, (d) 45 hours, (e) 60 hours, (f) 75 hours, (g) 90 hours, (h) 105 hours, (i) 120 hours, (j) 135 hours.

Considering the results of microstructural characterization and density measurement of the ball-milled reinforcement, various compositions of SiC:RHA:Pr_6O_{11} as 6:2:0.4, 6:2:0.8, and 6:2:1.2 are finally ball-milled for 105, 120, and 135 hours to match the density of the combined reinforcement proportionate to the AA6351 matrix and utilized for the fabrication and study of the rare earth modified AA6351 hybrid composites.

Characterization of AA6351 Hybrid Composites

Density and Porosity Measurement

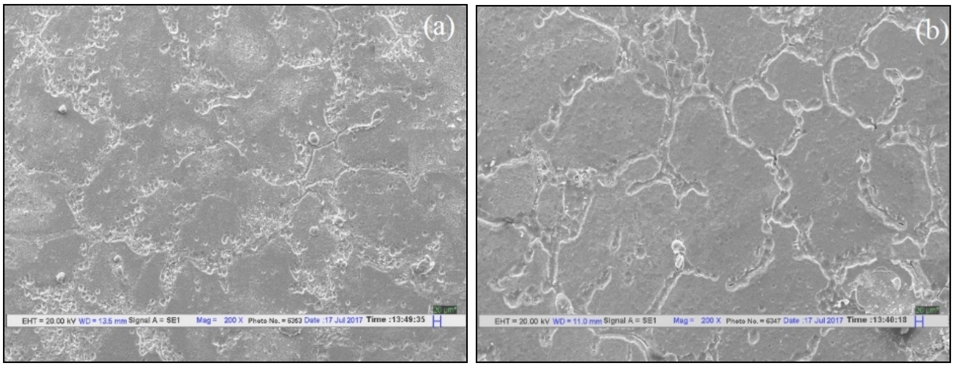
The measured density and estimated porosity level of the developed AA6351 hybrid composites are presented in Table 3. The estimated percentage porosity of the AA6351 hybrid composites varies from 1.144% to 1.399%. The results exhibited that the percentage of the estimated percentage porosity of the composites increased with the increased content of Pr_6O_{11}. The results also indicated that, in spite of using RHA as one of the reinforcements and stir-casting as a fabrication technique, the achieved value of maximum percentage porosity was 1.399%, which is less than the maximum acceptable value (4%) for cast aluminium matrix composites (Kanayo et al. 2013). This increase in density of the developed composites was due to the introduction of high density Pr_6O_{11} as the constituent of the reinforcement.

Table 3. Density and Porosity Measurement of AA6351 Hybrid Composites.

Sample Designation	Theoretical Density (g/cm^3)	Experimental Density (g/cm^3)	Estimated Percentage Porosity
A11	2.709	2.678	1.144
A12	2.735	2.702	1.207
A13	2.761	2.725	1.304
A14	2.787	2.748	1.399

Microstructural Characterization

Figure 5 (a–d) represents the SEM images of the rare earth modified (0.4, 0.8, and 1.2 wt.%) AA6351 hybrid composites. A uniform distribution of the reinforcement can be seen in the SEM images. Considering Figure 5 (a), SEM image of AA6351 hybrid composite with no inclusion of Pr_6O_{11} in it, the grains are quite randomly distributed. The SEM images of AA6351 hybrid composites with the inclusion of 0.4 wt.% and 0.8 wt.% of Pr_6O_{11} clearly show the grain refinement as shown in Figure 5 (b-c). With the further addition of Pr_6O_{11}, an equiaxed structure with more refined grain boundaries is obtained as presented in Figure 5 (d).



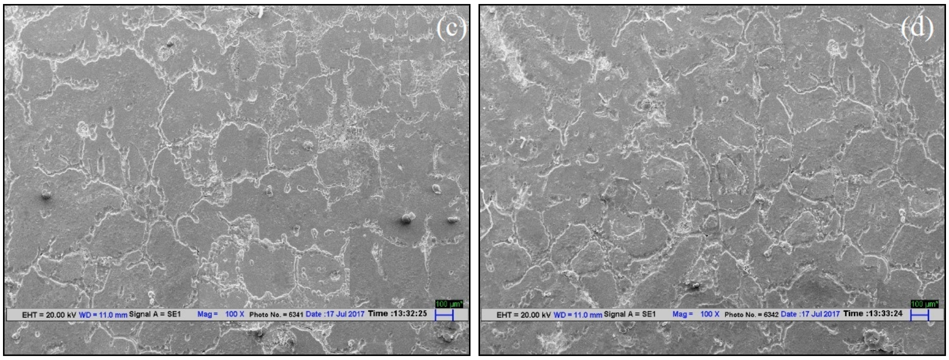


Figure 5. SEM images of AA6351/ 6%SiC/ 2%RHA Hybrid Composite: (a) 0 wt.%, (b) 0.4, wt.% (c) 0.8 wt.%, and (d) 1.2 wt.% Pr_6O_{11}.

Mechanical Characterization

The results of microhardness and tensile strength of the hybrid composites are presented in Figures 6 and 7, respectively. An increment trend of hardness and tensile strength values with the increased content of Pr_6O_{11} is observed during investigations. The best results of hardness (104.67 Hv) and tensile strength (218 MPa) are achieved for the A14 designated composite, having composition as AA6351/SiC:RHA 6:2/1.2% Pr_6O_{11}. One of the reasons for this improvement in the mechanical properties of the developed hybrid composites is the increased content of ball-milled reinforcement. The dislocation density increased with the inclusion of this ball-milled reinforcement due to the thermal inequality of reinforcement and the matrix alloy. An increment in this dislocation density resists the plastic deformation and leads to the improvement in the microhardness and tensile strength of the developed hybrid composites.

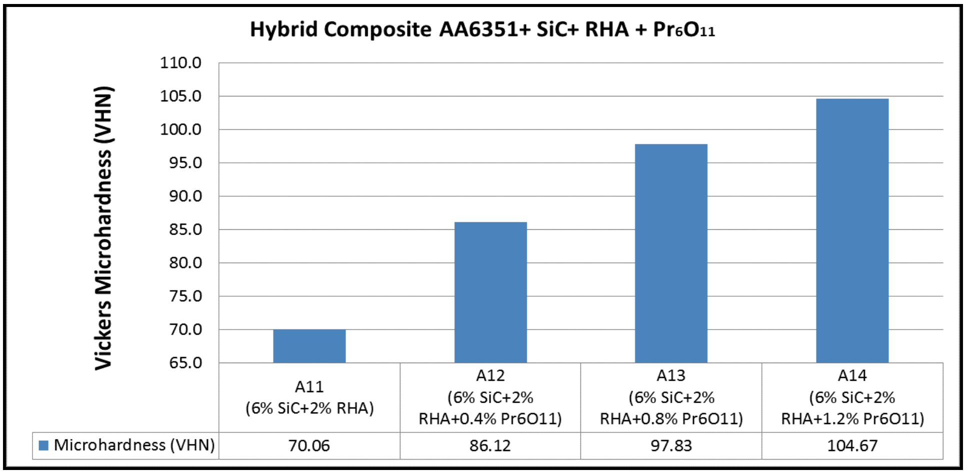


Figure 6. Variation of Microhardness of AA6351 Hybrid Composites.

This inclusion of rare earth element (Pr_6O_{11}) also enhanced the mechanical properties of the fabricated hybrid composites. The addition of rare earth element resulted in the refinement of grain structure, which finally reduced the interspacing between the molecules. This reduction in the interspacing improved the interfacial bonding between the grains of matrix and prevented the sliding of grain boundaries. This may be the main reason of improvement in hardness and tensile strength of the hybrid composites with the inclusion of Pr_6O_{11}.

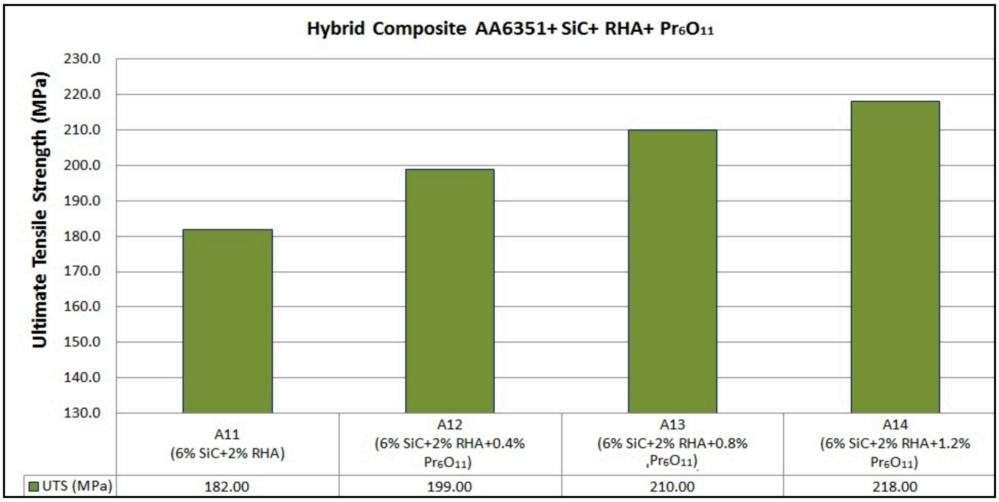


Figure 7. Variation of Tensile Strength of AA6351 Hybrid Composites.

Wear Behaviour Analysis

The variation of specific wear rate of fabricated composites with respect to the applied load is presented in Figure 8. It is clearly visible from the results that the specific wear rate decreased (i.e., improvement of wear resistance) with the increase in the percentage content of rare earth element and applied load as well.

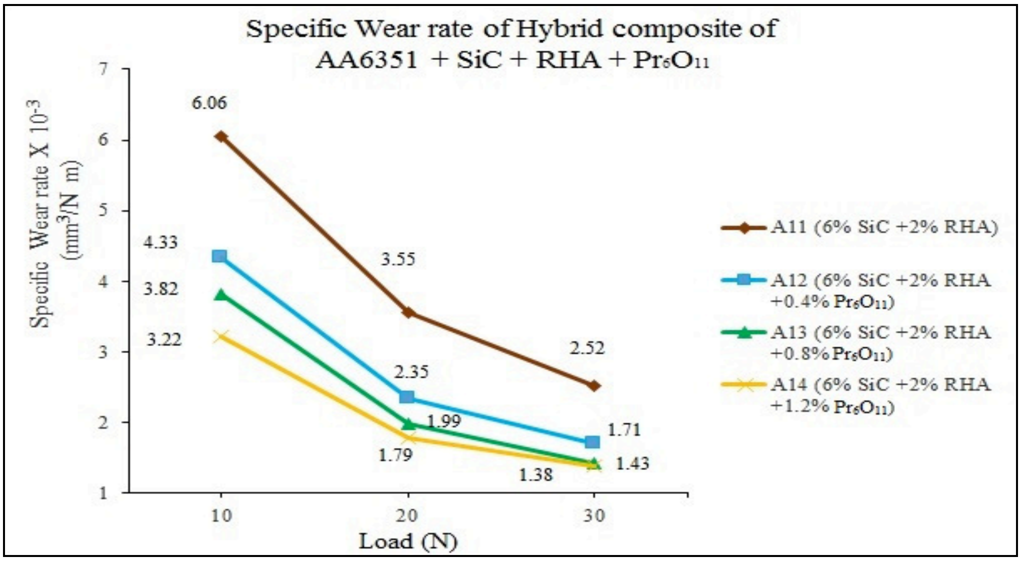


Figure 8. Variation of Specific Wear Rate of AA6351 hybrid composites.

The enhancement in the hardness and strength of the fabricated composites is one of the reasons for this improved wear resistance. Another reason of this improved resistance is the formation of a layer formed by the crushing of the reinforcement at the interface of the pin and the disk. This formed layer acts like a shield between the pin and disk and reduced the wear rate of the matrix material (Nurani et al. 2015).

COST ESTIMATION

The approximate price for AA6351 alloy and SiC has been considered in Indian Rupees (INR) 290/- and INR 800/- per kilogram, respectively, for the cost estimation. The cost of RHA has been considered as nil, because the rice husk is available for free, and a very minutest cost was associated for the production of rice husk ash. An approximate cost of INR 3,456/- per 100 gm has been considered for Pr_6O_{11}. Considering the same cost of fabrication of composites, a cost estimation of the produced AA6351 hybrid composite and the rare earth modified AA6351 hybrid composites is presented in Table 4.

Table 4. Cost estimation of AA6351 Hybrid Composite and Rare Earth modified AA6351 Hybrid Composites.

Sample Designation	Composition ($SiC:RHA:Pr_6O_{11}$)	Estimated Cost (INR)
A11	6:2:0.0	314.80
A12	6:2:0.4	451.88
A13	6:2:0.8	588.96
A14	6:2:1.2	726.04

Comparing the cost of hybrid composites A11 and A14 composition (composite that has shown the best performance), a very small difference in cost is there. On the other hand, the overall performance of composite having A14 composition is much superior than the performance of composite having A11 composition.

CONCLUSION

The rare earth element (Pr_6O_{11}) was successfully incorporated for the fabrication of AA6351/SiC:RHA 6:2/Pr_6O_{11} hybrid composites via stir-casting route. The hybrid composite having composition as AA6351/SiC:RHA 6:2/1.2 wt.% Pr_6O_{11} has shown the supreme microstructural, mechanical, and wear resistance performance. The hardness value of rare earth modified AA6351 composite improved from 86.12 Hv to 104.67 Hv, whereas the tensile strength value increased from 199 MPa to 218 MPa. The wear resistance of the hybrid composites also improved with the inclusion of Pr_6O_{11}. An outstanding improvement in the overall performance of the AA6351 hybrid composites was recorded with the inclusion of a small amount of Pr_6O_{11}.

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