Visual Abstract

Mechanical behavior and fractured surface analysis of bauxite residue and graphite reinforced aluminum hybrid composites

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ABSTRACT. Composite materials application areas have gradually grown, allowing them to reach and conquer new markets from consumer products to specialized niche applications, advanced composite materials make up a significant portion of the engineered materials industry. The purpose of this study is to investigate the mechanical properties of Aluminum (Al), Red Mud particle (RMp), Graphite particle (GRp) hybrid composites. The different combinations of Rm and Gr wt. % were used to prepare Al-Rm-Gr and Al-Gr-Rm hybrid composites. A stir casting technique is employed to prepare the various composite series. The mechanical properties namely Ultimate tensile strength, Compressive strength and Hardness of prepared hybrid composites are tested as per the ASTM standards to know the influence of reinforcements in Al-8011 alloy. Synthesis of Aluminum-Red Mud-Graphite hybrid composites done by Stir casting method. Drastic reduction in grain size (Grain refinement) was observed in Scanning Electron Microscopic images of fractured surfaces of the tensile specimens, with addition of RMp and GRp to the matrix alloy thus soft alloy is turned into hard and brittle material. Among all the compositions of hybrid composites series AG8R10 was observed to be higher compressive strength and hardness while AR8G10 has higher ultimate tensile strength.

KEYWORDS. Al-8011; Red Mud; Graphite; Stir casting.

OPEN ACCESS

Citation: Anil, K.C., Kumarswamy, J., Reddy, M., Prakash, B., Mechanical Behaviour and Fractured Surface Analysis of Bauxite Residue & Graphite Reinforced Aluminium Hybrid Composites, Frattura ed Integrità Strutturale, 62 (2022) 168-179.

Received: 14.06.2022
Accepted: 19.08.2022
Online first: 24.08.2022
Published: 01.10.2022

INTRODUCTION

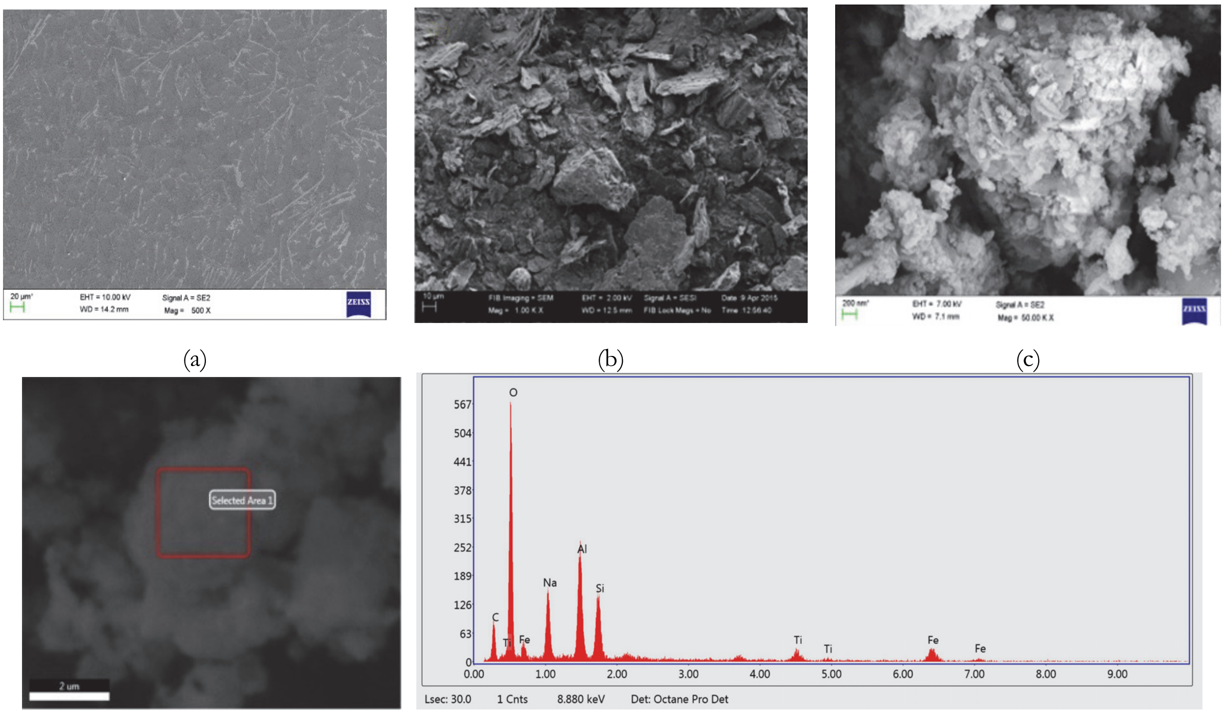
In present-day innovation, the idea of combining two distinct materials has gained more significance: in terms of directional properties, wear resistance, strength to weight ratios, stiffness, corrosive and thermal behaviour, etc., the mixture has its unmatchable properties. The principal attraction of modern composite materials is that they are lighter, stronger, and stiffer than anything made ever before, and they found application in space crafts, supersonic flights, etc. To achieve a good combination of strength, rigidity, durability, and density, traditional monolithic materials have limitations. Composites are the most exciting materials of recent interest to address these shortcomings and meet the ever-growing demand for modern-day technology. Although, the composites have their own limitations in the field of corrosion compressive stiffness, formability etc. As part of this research work, the survey is performed to learn the matrix materials, reinforcements, production processes, standards of specimens, physical, chemical, wear, and mechanical behaviour of composites. The overall savings of compound structures over metal equivalents and the economic costs, service and maintenance were demonstrated by at least 20 percent [1]. As data and life-cycles of composite structures become available, robust, durable, dimensionally integral, fatigue-resistant, and easy to maintain and repair can be stated safely. Since composites have new applications in many industries such as aerospace, automotive, etc., they require less costly methods of processing that meet massive market growth and recycling prospects [2] have to be addressed [3]. When aluminum is recycled, the energy consumed is documented to be only about 5% of that needed in the primary production of aluminum [4]. However, some drawbacks associated with aluminum recycling, such as the presence of impurities such as grease, dirt, moisture, etc., greatly affect the mechanical characteristics of the recycled material. A selection of the parameters and procedures incurred in the production method can resolve this issue, because they could lead to the development and accumulation of harmful intermediate phases [3-5]. In developing an effective MMC material, there are several interdependent variables to consider. Since the matrix and reinforcement material properties are determined by the upper bound on the MMC properties, careful selection of these components is important. This uniform distribution depends on the wetting agent, the matrix's porosity, the chemical reaction among matrix and reinforcement, preheat temperature of reinforcement, stirring temperature, stirring time and speed, stirrer geometry, etc. [11-12]. H.B. Bhaskar et. al. [15] have prepared MMC using Aluminium 2024 as a matrix and beryl particles as reinforcement by stir casting route, where the stirring is done at a speed of 350 rpm for 8 min. Among all the fabrication techniques used to fabricate the MMCs the stir casting is most economical for mass production. For this reason, stir casting is the most commercial processing technique employed for developing AMCs [13-14]. Wettability is a liquid's ability to disperse on a solid surface, which indicates the degree of intimate interaction between a liquid and a solid. The particles having a high affinity for oxygen will increase wettability. Magnesium (Mg) acts as a reactive element as well as a good wetting agent (surfactant) with aluminum alloy and helps to fulfil the above requirements [17]. Mg as a wetting agent plays a very vital role in the synthesis of AMCs. Mg helps to thin the gas layer on the dispersoid surface of particles by scavenging oxygen.

MATERIALS AND EXPERIMENTAL DETAILS

Matrix and Reinforcement

The research work on MMCs focuses on the matrix phase of aluminium alloy. The combination of ductility, lightweight, resistant to corrosion, environmental strength and useful mechanical qualities is promising. Aluminum has a density of 2.7 g/cm^3 and a melting point of 660.3 °C as a lightweight material. The melting temperature is high enough to meet many applications, yet low enough to allow reasonable and several processing methods. As aluminum can accommodate various reinforcements like particles, fibres, whiskers, etc., the researcher has concentrated on AMCs because of their availability, low fabrication cost, and relatively isotropic properties [9]. The most common aluminum alloys used in the production of MMCs are LM-25, 1100, 2024, 3014, 6061, 6063,7072, 7075, 8011 and etc [6,7,8,10]. They fabricated sandwich panels using AA8011 and AA1100. The bonding is achieved by using epoxy resin-based adhesive through a rolling process. The AA8011/PP/AA1100 sheets are 0.91mm, 1mm, and 0.91mm thickness, respectively. The AA8011/PP/AA1100 sandwich sheets were subjected to a tensile and flexural test to determine the respective strength parameters. The results show that there are reasonably good agreements between the experimentally measured and the calculated values. Al-8011 is an otherwise – unclassified alloy of aluminum. It has a high ductility compared to other Al-alloys. The main alloying element of Al- 8011 is Fe and Si and contains appreciable amounts of tin & lithium [9]. Thus, the present research is aimed to prepare the hybrid composite using Al-8011 alloy.

Developing and implementing effective storage and disposal programs remains essential as the inventory grows year by year. The chemical and physical properties of bauxite residue vary by the nature of the ore and the Bayer process's effect. The geographical location of ore and operating procedure of individual refineries will impact the residue's PH value. Thus the Bauxite residue management is a major issue for refineries to find best practices globally to store and achieve less social and environmental impacts during operation and post-closure [22]. Adopting the best practice involves many challenges and risks influenced by government policies, regulatory frameworks, geographical and climatic conditions, and community factors. The best practice is not a single solution that involves disposal, long-term storage, and filtration re-use options, etc. Rudraswamy et al. [23] have tested the properties of the concrete block made up of RM at different wt. %. Results show that the strength characteristics like impact strength, compressive strength, flexural strength, tensile strength, and shear strength are increased up to 10% replacement level. Ramesh et al. [32] also examined the properties of RM concrete and stated that the splitting tensile strength and compressive strength decreases with an increase in red mud content, and the optimum percentage of cement replacement by weight is found to be 25%. By this percentage replacement, one can have strength equal to the strength of controlled concrete.



(a) (b) (c)

(d)

Figure 1: SEM micrographic image of (a) Al-8011 alloy matrix (b) Graphite particles (c) Red mud particles (d) EDAX of the red mud particles.

The monocrystalline graphite has a theoretical density of 2.26 g/cm^3 and has a lattice structure of the hexagonal cell. Graphite is a material that has mechanical properties close to ceramics like excellent chemical resistance, thermal stability, and high electrical conductivity. Thus, it is commonly used in the electro-metallurgy sector. Its applications in this field are defined by its chemical and physical properties and secondly, by its suitability as a building material for machinery. Barekar et al. [25] suggested that conventional/traditional methods often yield very lower strength and ductility agglomerated structures. The well-established and high-shear disperse mechanisms of a twin-screw mechanism are adapted innovatively to address the agglomerate problem of a cohesive force with a melting-conditioned high-pressure die casting (MC-HPDC). The rheo approach adopted greatly improved reinforcement distribution in the matrix with a strong interfacial link. A good combination of enhanced ultimate tensile strength (UTS) and tensile elongation (e) compared to composites provided by traditional methods is obtained. Dunia Abdul Saheb et al. [24] Developed MMCs, graphite particulates MMCs for aluminum based, silicon carbide particulate to create a standard low cost MMC manufacturing method and obtain the homogenous ceramic material dispersion. Fig. 1 shows the SEM images of matrix Al-8011 alloy and reinforcements graphite flakes and Red mud particles used to prepare composites and EDAX of red mud particles. From the EDX of the red mud particles is shown in Fig. 1(d) it can be seen that the presence of different elements like silica, iron, aluminium, titanium, calcium, as well as an array of minor constituents, namely: Na, K, Cr, V, Ni, Ba, Cu, Mn, Pb, Zn etc. thus, red mud is potential reinforcement to use in preparation of metal matrix composites. Also, the presence of oxygen in sample is quite common and may originate from the material itself, from the environment and other surrounding as well from the sample preparation and storage [53].

Casting and Coding

Stir casting is an ideal route for processing AMCs compared to other fabrication techniques [15-21, 35, 46-51]. Al-8011 alloy is melted in the electrical resistance furnace to attain 750°C; the melt was agitated with the help of Zircon (Zr) coated stainless steel stirrer to form a good vortex then the C_2Cl_6 – solid hexachloroethane was added to remove the entrapped gases inside the melt and stirring is done at a speed 50 rpm for a 5 min to ensure proper mixing of the degassing agent in the melt, latter slag was removed from the molten metal. At the temperature of 700°C, the preheated reinforcement particles with a wetting agent Mg [17] were added with different wt. % into the vortex. After adding the reinforcement and wetting agent to the melt, a mechanical stirring was done at 150 rpm for 10 mins to obtain a proper mixing and uniform distribution of particles in the matrix alloy. Then the mixture is kept in the furnace to get the required temperature for pouring. Before pouring the molten metal into the mould, cover flux (NaCl 45% + KCl 45% + NaF 10%) was added to the molten metal to reduce the atmospheric contamination. Since Mg's surface tension (0.599N/m) is lower than that of Al (0.760 N/m), the addition of Mg reduces the surface tension of the molten Al.

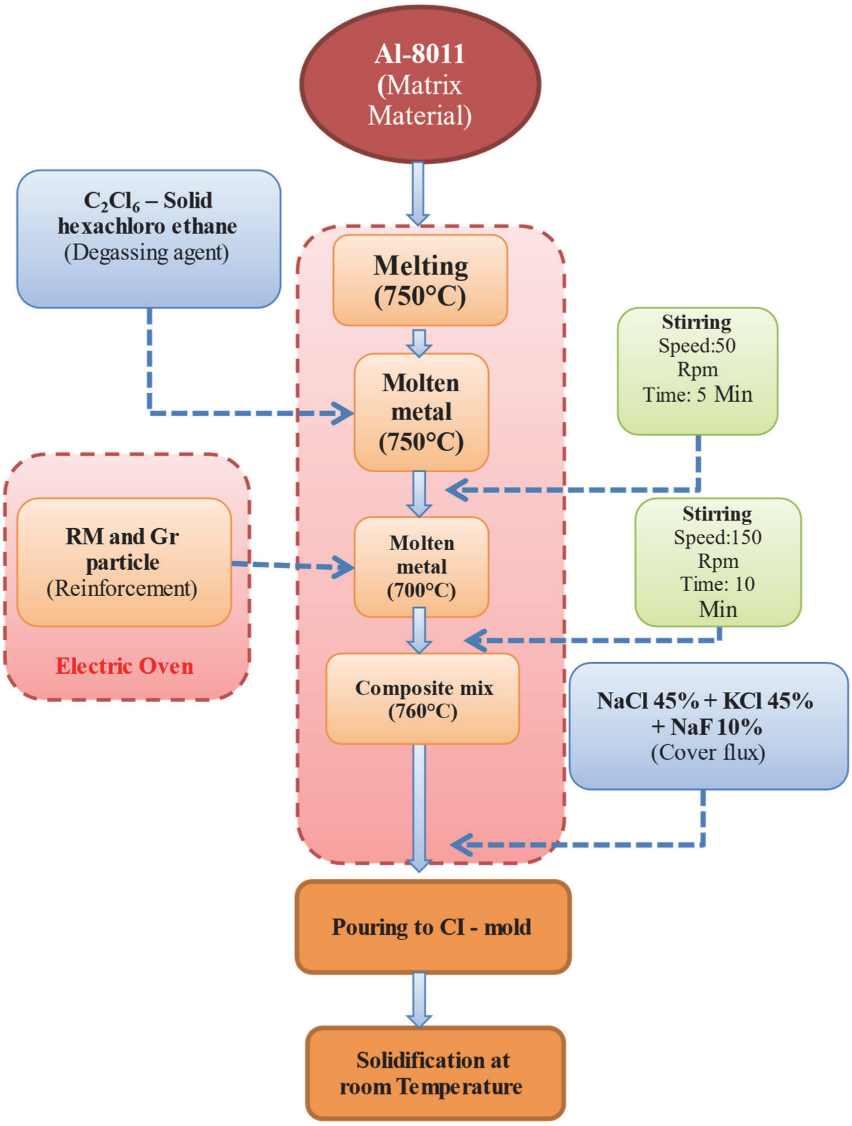


Figure 2: Flow diagram of steps followed to cast the hybrid composites.

The mechanical and tribological properties of both Al-Rmp and Al-Grp composites were examined and found higher UTS value and good wear resistance in Al-8% Rmp and Al-8% Grp composites [50,52] hence the hybrid composites series were prepared by keeping 8 wt. % for both reinforcements constant. The combination and code of Rm wt. % and Grp wt. % used to Prepare Al-Rm-Gr & Al-Gr-Rm Hybrid Composites are tabulated in Tab. 1

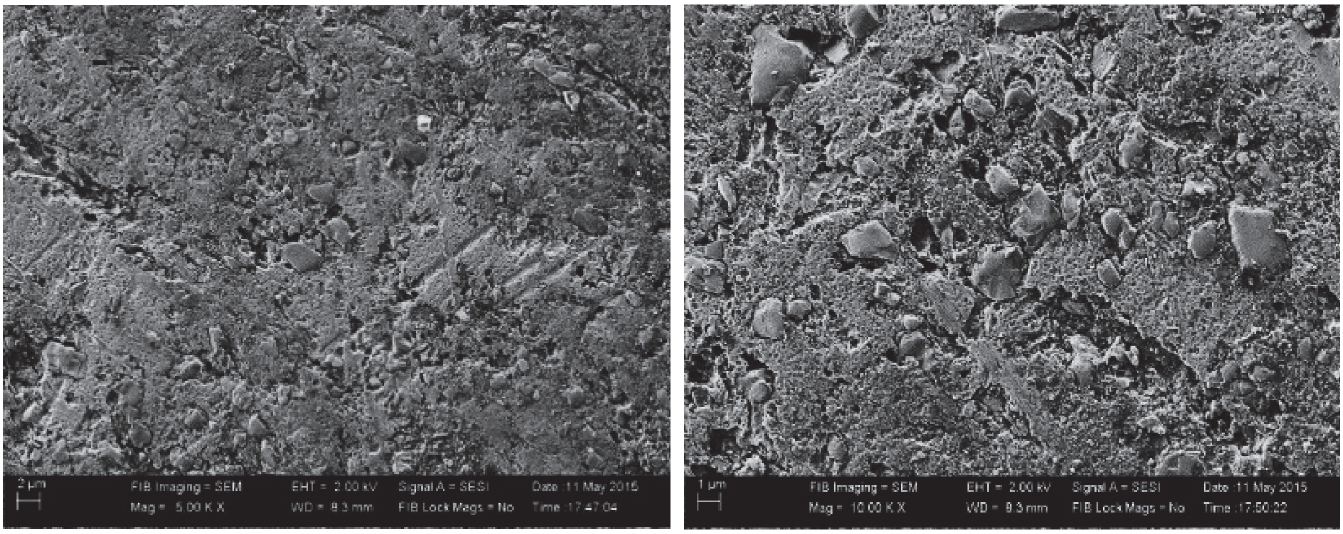
Compositions	Code	Compositions	Code
Al + 8% RMp + 2% Grp	AR8G2	Al + 8% Grp + 2% Rmp	AG8R2
Al + 8% RMp + 4% Grp	AR8G4	Al + 8% Grp + 4% Rmp	AG8R4
Al + 8% RMp + 6% Grp	AR8G6	Al + 8% Grp + 6% Rmp	AG8R6
Al + 8% RMp + 8% Grp	AR8G10	Al + 8% Grp + 8% Rmp	AG8R8
Al + 8% RMp + 10% Grp	AR8G10	Al + 8% Grp + 10% Rmp	AG8R10

Table 1: The combination and code of Rm wt. % and Grp wt. % used to Prepare Al-Rm-Gr & Al-Gr-Rm Hybrid Composites.

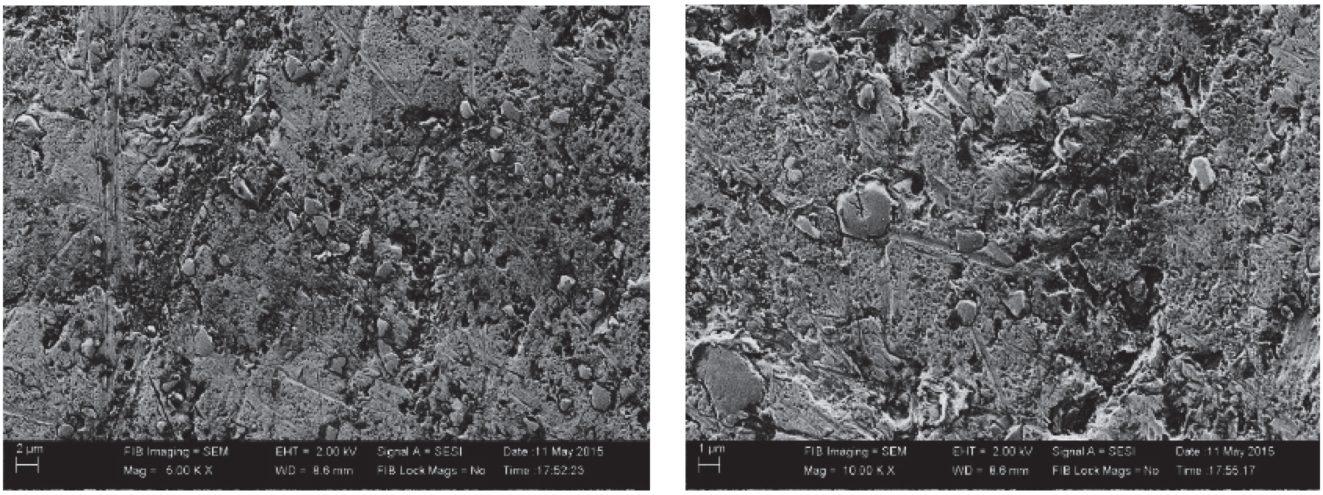
RESULT AND DISCUSSION

Microstructure

A few/typical samples are taken for SEM analysis and Fig. 3 shows that the red mud and graphite particles are uniformly well distributed within the Al-8011 matrix material. No aggregates of the red mud particles can be seen in the mixture in Al-RMp-Grp, and Al-Grp-RMp hybrid composite by this, we can conclude that the wetting agent Mg. and casting parameters used to fabricate the composites are suitable to cast the said composite series. The area fraction also increases as the reinforcement percentage increases, as shown in Fig. 3 (b). There is also an increase in mechanical properties. The interfacial bonding of hard particles with the base alloy can be due to this Strong interfacial bonding can be obtained before adding the same by proper pre-heating of reinforcement, as stated by Hitesh Bansal [33]. Fig. 3 (b) shows a homogeneous mixture of Gr particles in Al-8011 alloy. However, Gr. particles' agglomeration in some regions is visible in Fig. 3 (c, d). This is because of the lower density of Graphite compared to red mud, which tends to float in the melt and settled together in the matrix alloy when poured into a mould or due to the presence of porosity associated with it [34,47,50], entrapped air and moisture in the graphite particles.



(a) (b)



(c) (d)

Figure 3: SEM micrographs of (a-b) Al-RMp-Grp hybrid composite, (c-d) Al-Grp-RMp hybrid composite.

Ultimate Tensile strength

The UTS is affected by a variety of interconnected and dynamic factors. Various variables are reported to have a discontinuous effect on the strength of the composites, such as the distribution and number of particulates in a matrix, the mechanical and physical characteristics of the matrix, the strengthening of the particulates, and the link between matrix and rehabilitation. Various mechanisms for strengthening the force in discontinuously strengthened MMCs have also been proposed [29,54,55]. Fig. 4 shows the effect of particulate addition on the UTS of the composites. The specimens were prepared and tested as per the ASTM E8 standards and average of 5 values is plotted to known the variations in results. Due to the increased area of bonding at the interfacial region of the matrix and the reinforcement in hybrid composites, the UTS of the hybrid composites increases monotonically as the particulate content increases. Other researchers have found that adding ceramic particles to aluminium alloys enhances their strength, wear resistance, and hardness [26-28]. It is also observed with the addition of ceramic particles, the alloy becomes more brittle and the same is shown as %, of elongation.

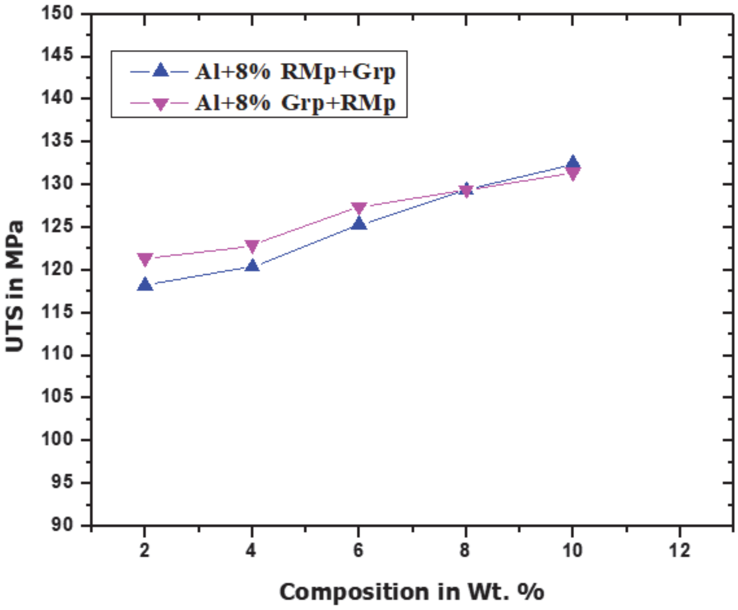


Figure 4: UTS of Al-RMp-Grp and Al-Grp-RMp hybrids.

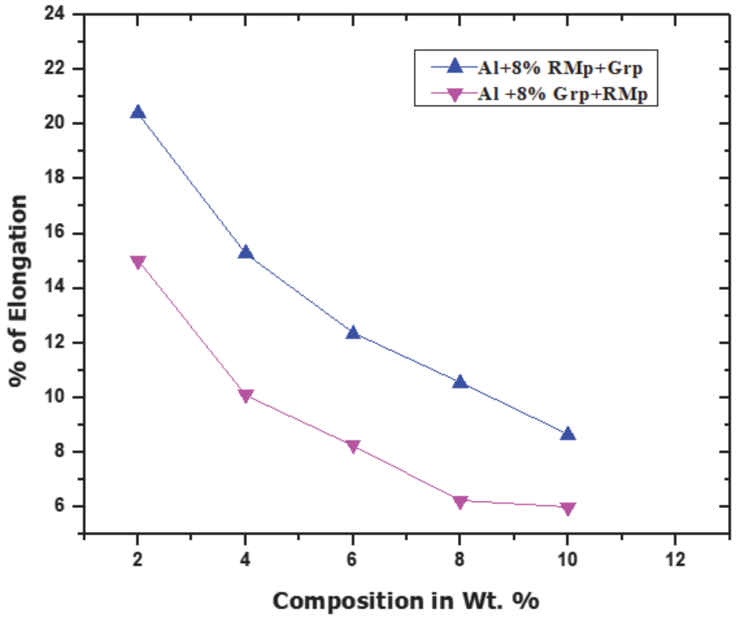


Figure 5: Percentage of elongation of Al-RMp-Grp and Al-Grp-RMp hybrid composites.

An increase in the dislocation pileup as the particle content is increased. Thus, there is a plastic flow restriction due to the particles' random distribution in the matrix. Fig. 5 shows that increase in the reinforcement wt. % leads to a decrease in elongation of the hybrid composite. The elongation of the Specimens is measured using extensometer in the test rig. This is due to an increase of brittleness in the composite, which leads to less plastic deformation. Also, the decreased interparticle spacing, due to the increasing volume percent of reinforcement, creates increased resistance to dislocation motion, contributing to the enhanced strength of the composites [30,31]. The addition, RMp and Grp decrease the Aluminium’s ductility by increasing the hardness of the composites. The results obtained from different compositions of composite materials AR8G10 and AG8R10 hybrid composites, show higher UTS values regarding their composition series, as shown in Fig. 4. When we compare the overall composites series, the UTS of AR8G10 has increased 44.9% and stands higher among all where base Al-8011 matrix alloy have 91.405 UTS [47,50].

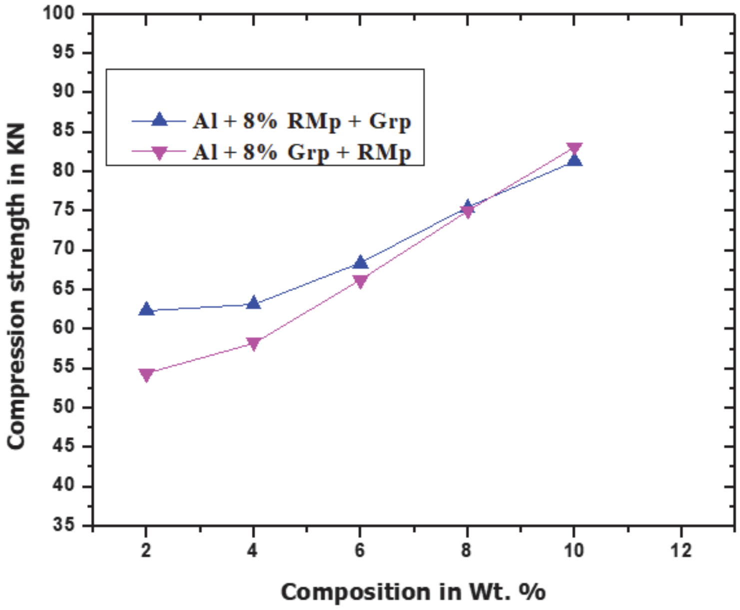


Figure 6: Compression strength of Al-RMp-Grp and Al-Grp-RMp hybrid composites.

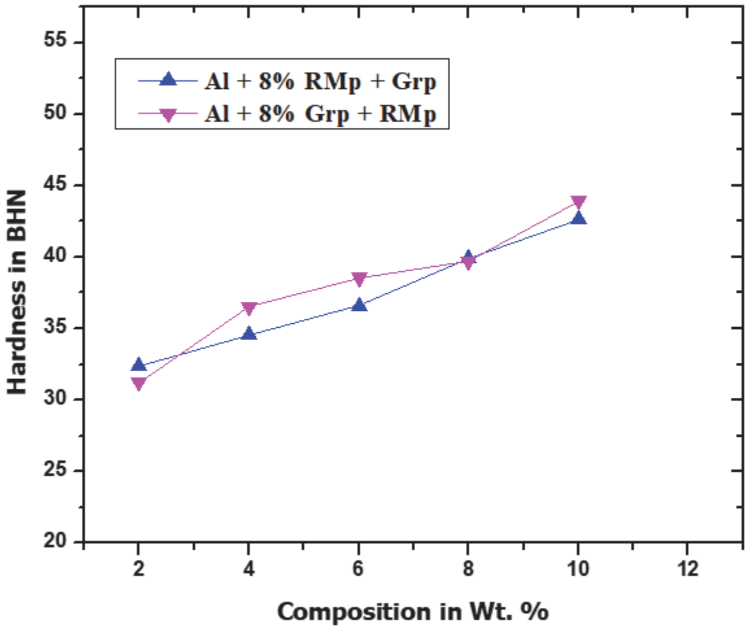


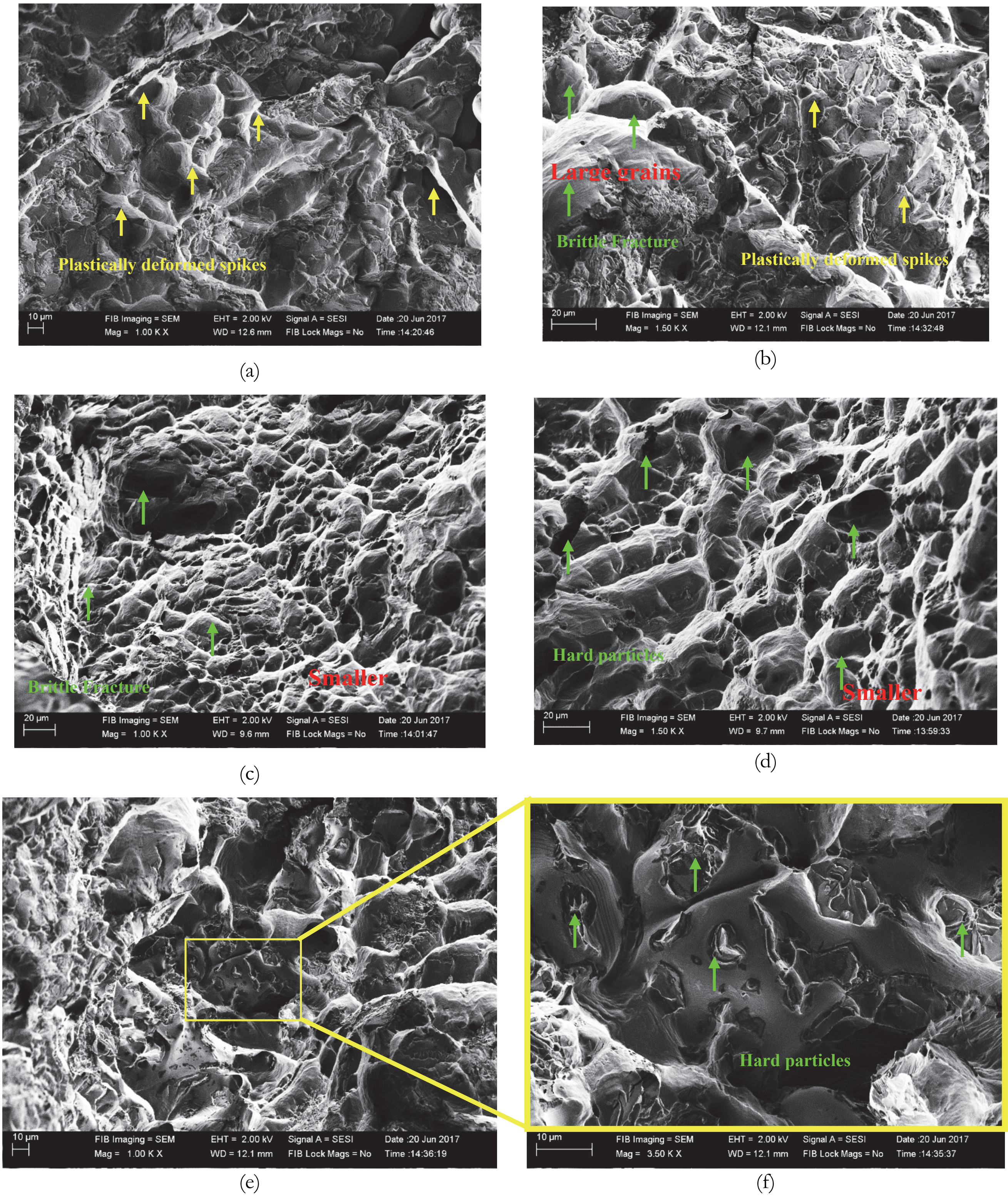
Figure 7: Hardness of Al-RMp-Grp and Al-Grp-RMp hybrid composites.

Compression strength

From Fig. 6, it can be shown that all the hybrid composite's compressive strength increases monotonically as the reinforcement material increases. The specimens for the compression test were prepared and tested as per the ASTM E9 standards. The increase in compressive strength is attributed to the decrease in the inter-particle spacing between the red mud particles since RM is harder than the Alloy Al-8011. The red mud particles' presence resists deforming stresses, thus enhancing the compressive strength of the composite material. The percentage of increase in compression strength is similar to the tensile strength and hardness of the composites. However, the incorporation of hard RMp into the composites allowed the composites of the metal matrix to act as brittle rather than ductile materials. Because RMp alone contains many ceramic constituents like Al_2O_3, Fe_2O_3, SiO_2, TiO_2, etc., the capacity of load-bearing of Al-RMp composites increased thus higher compression strength. Furthermore, ceramic elements have a lower thermal expansion than base alloys, resulting in the formation of dislocations at the matrix-reinforcement interface during solidification, which contributes to the composite's strength [50]. The graph also revealed that the Grp also plays a vital role in increasing the compression strengths of hybrid compositions by resisting the applied load. In Al-RMp composite series, it is observed that the increasing trend tends to follow the linear path. Composites with RMp particles have shown higher compression strength in the Al-Gr-RMp and Al-RMp-Grp hybrid composites. The maximum compression strength of 83.14 KN (118.4% higher than the Al-8011 base alloy [47,50] is obtained for the AG8R10 hybrid composite.

Hardness

The static indentation test was the test used in the present study to examine the specimens'. The specimens for the hardness test were prepared and tested as per the ASTM E10 standards. A ball indentor with a diameter of 10mm was employed in the hardness test, and a load of 500 N was applied for 30 seconds over specimens with a diameter of 15 mm at 5 separate sites, with average values recorded and plotted in Fig. 7. According to Seah et al. [27] and Sahin [28], the increased hardness is also attributed to the fact that the hard red mud particles act as barriers to the movement of the dislocations within the matrix. As the percentage of reinforcement varies by weight, the composite hardness increases monotonically and dramatically from 32.4 to 42.64 BHN in Al-RMp-Grp hybrid composite series and 31.25 to 43.94 BHN in Al-Grp-RMp hybrid series whereas the Al-8011 have 21.3 BHN [47,50]. The increase of hardness is due to the increased area of bonding at the matrix's interfacial region and the reinforcement and refinement of grain structure. Also, the increase in hardness can be attributed to the addition of red mud and graphite particles which impart strength to the matrix alloy by enhanced resistance to crack or penetration. Enough researchers also reported that the addition of hard particulates in metal alloys could lead to improved strength and hardness.



(a) (b) (c) (d) (e) (f)

Figure 8: SEM micrographs of a fractured surface of (a) Base alloy (b, c, d) Al-RMp-Grp hybrid composite, (e-f) Al-Grp-RMp hybrid composite.

Fracture surface analysis

Fig. 8 (a) shows that there are plastic deformation spikes on the fractured surface in the base alloy as it can see the ductile fracture. But Fig. 8 (b) shows a ductile to brittle transition, because after an added hard particle in the matrix, it can clearly see the plastic deformation spikes and the trans granular fractures on the surface. This is because matrix alloy becomes more difficult and brittle with the addition of reinforcements. Fig. 8 (c-d) shows a completely inter-granular fractured surface and the vacant seats of the reinforcements, partial breakage of hard particles. This shows that the Al-RMp-Grp and Al-Grp-RMp hybrid composite are harder and brittle than other composite series. Also, it is clear that the addition of ceramic reinforcement will reduce the matrix alloy's grain size, strengthening the matrix alloy. Fig. 8 (e-f) shows the fractured surface of the Al-Grp-Rmp hybrid composite sample. It is clearly showing the breakage of hard particles within the matrix alloy, which shows that the particles will restrict the movement/propagation of a crack in matrix alloys. Thus, the load withstanding capacity of the matrix alloy is increased with the addition of reinforcements. Many researchers [36-45] are also investigated the fracture specimens to observe the presence of reinforcement and type fracture.

CONCLUSION

This paper presents the different combination of reinforcements such as graphite and bauxite residue (red mud) used in the synthesis of Aluminium metal matrix hybrid composites and how it influences its performance. Aluminium-8011 alloy reinforced with combination of both RMp and Grp hybrid composites were successfully fabricated with fairly uniform distribution using conventional stir casting route. The addition of magnesium as a wetting agent with the RMp into the Al-8011 during casting has resulted in homogeneous distribution of particles. Dispersion of graphite and red mud particles in aluminum matrix improves the compression strength from 38.06 KN to 81.41 KN in case of AR8G10 and 83.14 KN in case of AG8R10 hybrid composites, The tensile strength of AR8G10 and AG8R10 hybrid composites are 132.46 MPa and 131.50MPa respectively whereas base alloy possess 91. 407 MPa. The composite hardness increases monotonically and drastically as the percentage of reinforcements rises by weight from 21.26 to 42.64 BHN in the Al-RMp-Grp hybrid composite series, and 21.26 to 43.94 BHN in the Al-Grp-RMp hybrid composite series. Red mud, the by-product of alumina refineries, can be effectively used to produce Aluminum Matrix Composites (AMC's) as a reinforcement material. Ductile to brittle transition is observed in fractured surfaces of the hybrid composites. Instead of traditional aluminum-intensive material, it can be used as possible reinforcement as it includes many other ceramic components, thereby saving about 12 percent of matrix material.

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