Effect of rubber ash on mechanical properties of Al6061 based hybrid FGMMC

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Abstract

The usage of rubber ash as a reinforcement material for aluminium composite has never been used, this work pertains to one such experimentation. In this work rubber ash and boron carbide in varying proportions to reinforce Aluminium based Hybrid functional grade metal matrix composite (FGMMC). The fabrication is done using the centrifugal casting method. The rubbish ash and B4C content are varied and the samples are tested to get the ratio with the optimal mechanical properties. The tensile strength of the Aluminium based Matrix Composites (AMC) seems to increase with an increase in % weight of rubber ash. Further analysis of the composite reveals that the B4C and rubber ash particles were evenly distributed in the AMC. This can be confirmed using SEM imaging. This work studies the usage of boron Carbide and rubber ash to reinforce the FGMMC by comparing its properties to conventional AMC’s. The mechanical properties along with the cost factor are weighed to arrive at a convincing solution.

Introduction

With the rise of the modern automobile industry in the 21st century, there have been high demands for materials. This demand for metals is more for aluminum owing to its lightweight and mechanical properties like hardness, tensile. Aluminum also has good elastic properties combined with a low density which is the requirement in the modern automobile and machine manufacturing industry [1, 2]. Due to such high demands, there has been an urge to develop aluminum alloys with high strength without sacrificing the low weight coefficient [3, 4]. This requirement of the current situation can be met by functionally graded material (FGM) [5]. The FGM has a transitional property that meets the functional requirement in the automobile industry [6].

The FGM’s have a great demand as they tend to meet the current requirements of the industry. Large scale production of the FGM’s can be hindered by solid or liquid state processing [7]. A simple and efficient way of manufacturing these FGM’s in liquid state processing is by centrifugal casting [8]. The issues that hinder the large scale production using centrifugal casting are proper bonding between the particulate reinforcement and the liquid aluminum alloy metal. The usage of finer particles may resolve this issue but could lead to clustering, hence overcoming these problems would mean a viable solution for centrifugal casting production of FGM’s in a cost-effective manner [9].

It is important to have a material with lower density, this reduced density means reduced weight. Reduced weight in automobiles accounts for higher efficiency. The automobile industry also demands higher strength to absorb the forces transmitted to the vehicle, meaning, the reduction in density must not compromise the strength of the material. The design of FGM’s effectively involves choosing the correct composites to obtain optimal density, hardness, and tensile strength [10]. Homogeneity of the composite is increased by the uniform distribution of the lower density reinforcements around the matrix when compared to the high-density reinforcements [11]. In centrifugal casting, the high-density particles settle towards the outer phase and lower density reinforcements are settled in the inner phase of the castings. This hybrid matrix composite results in clustering and random distribution of the reinforcement particles [12]. In these types of FGMs, the hardness
increases from the inner surface of the casting towards the outer surface of the casting. Conversely, the elasticity gradually decreases from the inner surface of the casting towards the outer surface of the casting [13]. The heterogeneous property of the AMC is now increased due to the hybrid reinforcement distribution [14].

The combination of high hardness and toughness combined with low density is exhibited by boron carbide and aluminum composites. There are many methods by which these Metal Matrix Composition (MMC) can be manufactured, reaction synthesis being one effective manufacturing method for these MMC’s. Reaction synthesis has been deemed a cost-effective and effective method of manufacturing such as MMC’s [15–23]. The gradual change in properties such as young modulus, hardness, wear resistance, etc, can be effectively achieved using centrifugal casting. The formation of such MMC’s demands a difference in density and this can be achieved using centrifugal casting [18, 19]. In this method of centrifugal casting, a composite material is preheated and poured into a cast in a liquid state. The cast is under constant centrifugal force which gives the gradation in material property, by allowing the outer walls of the casting to be more densely packed compared to the inner wall. FGM with alumina silicon carbide, titanium carbide, and titanium diboride reinforcements are enumerated in a lot of research work. This work deals with Al–B₄C monolithic composite since B₄C possesses many properties that will make the reinforcement harder and more stable [23, 24].

AMC’s are reinforced using various waste or scrap materials to reduce the cost of production. Some literature shows that SiC and rice husk ash have been used as reinforcements in the fabrication of AMCs [25]. Fly ash has been used as a reinforcement in the manufacturing of LM6 Al alloy to enhance its properties for better performance [26, 27]. Similarly silicon carbide and rice husk ash are used in the fabrication of Al alloy to improve the performance of the AMCs by enhancing its mechanical properties [28]. Other studies point out the effects of reinforcements on the mechanical and tribological properties of the composites, for instance, the addition of rice husk ash by around 10%–15% weight concentration improves the physical properties of the composites [28–30]. Tires lose their ability to provide adequate friction after they are worn out and are mostly discarded. This waste when left as such poses great danger to the environment. The cost of lightweight materials has been increasing whereas the powdered form of this wasted rubber is readily available at a low cost. This makes rubber powder a viable and cheap means of lightweight reinforcements in MMC. Recycling of waste tires and using them as an additive material in the automobile industry has become common practice recently [31]. Rubber ash reinforcements offer good mechanical properties when used as lightweight reinforcements [32].

From the literature mentioned, it can be concluded that many attempts were made to use the wastes from agricultural products and scraps from industries as reinforcement for AMCs. These reinforcements have proved to improve the properties of the composites while reducing the production cost. In this work, Hybrid Metal Matrix FGM Composite is made from commercially available rubber ash, boron carbide and 6061 Aluminum. The Al–B₄C–Rubber ash matrix is used to obtain a composite that has high strength, ductility, and low density. The use of a Scanning Electron Microscope would give us the density of the matrix apart from that the hardness and tensile are also estimated. The experimental procedure has shown in figure 1.

Materials and methods

The material selection is an especially important process to make sure that the study complies with proper standards. The chosen base material is 6061 Aluminum alloy and its composition is shown in table 1. The considered reinforcements are boron carbide (B₄C) that has high ductility and rubber ash due to its mechanical properties. The density of B₄C is 2.52 g cm⁻³ and the density of rubber ash is 0.641 g cm⁻³. There are different samples obtained by using different % weight composition in the matrix and are shown in table 2. The size of the particles chosen for this study ranges between 15–40 μm.

Procedure

Rubber ash and Boron Carbide are preheated to 400 °C and 1100 °C in a ceramic pot before the melting of Aluminium. Using a muffle furnace Al6061 was melted in a graphite crucible at 800 °C, meanwhile degassing agents, flux was added to remove unwanted gases and ashes respectively. After the melting of aluminium, then it poured into another graphite crucible, now the preheated Rubber ash and Boron Carbide are added in the respective weight combinations as shown in table 2 into the aluminium melt. During the pouring, it is stirred well using a graphite rod. The stirred melt is poured into a mould of the horizontal centrifugal machine, which was preheated at 300 °C and rotated at 1500 RPM(Constant).

Metallurgy and metallography specimen preparation

The cast samples are fabricated as per the ASTM standard with the help of wire cut EDM and milling. The tensile strength is tested as per E8-04 ASTM standard and the hardness and density are evaluated under E407 and B962-15 ASTM standards, respectively. To calculate the actual density of the fabricated composites, the
Figure 1. Set-up line diagram.

Table 1. Chemical composition of 6061 aluminium alloy (wt%).

|   | Mg   | Si   | Cu   | Zn   | Fe   | Al   |
|---|------|------|------|------|------|------|
|   | 0.8–1.2 | 0.4–0.8 | 0.15–0.4 | 0.25 | 0.7 | Remaining |

Table 2. Composition of samples.

| Sample | Rubber Ash (%wt.) | Boron carbide (%wt.) | Al6061 (%wt.) |
|-------|-------------------|----------------------|---------------|
| 1     | 0                 | 0                    | 100           |
| 2     | 0                 | 4                    | 96            |
| 3     | 3                 | 4                    | 93            |
| 4     | 6                 | 4                    | 90            |
| 5     | 9                 | 4                    | 87            |
| 6     | 12                | 4                    | 84            |
| 7     | 15                | 4                    | 81            |
Archimedes principle was used. The mass of the samples was measured twice, where the mass was first measured by direct weighing and then by suspending the composites in distilled water. The density of the composites was estimated using the following expression:

$$\rho_c = \rho_w \left\{ \frac{M_a}{M_a - M_w} \right\}$$

Where $M_a$ represents the mass of composite by direct weighing, $M_w$ represents the mass of composite in distilled water, and $\rho_w$ denotes the density of distilled water.

This specimen is prepared for a metallography test to study the particle distribution of the composite. The interfacial layer is enhanced by a special etching technique where the sample is immersed in a 20% HF solution for 3 min and cleansed by methanol. This technique is used since the interfacial layer becomes unreadable after polishing where the layer is removed in the polishing process. The point count method determines the % Volume of the rubber ash and Boron carbide particles.

### Results and discussion

#### Chemical composition of rubber ash

The chemical composition of rubber ash has been determined by x-ray fluorescence conducted in the laboratory. The findings of the tests are tabulated in table 3. The observations show 14.6% of zinc oxide in rubber ash even though it increases the settling time of the FGM it adds to the improvement of the mechanical and physical properties of function graded composite [33]. Apart from zinc oxide, Silicon dioxide and Sulphur trioxide are present in larger proportions and they further enhance the properties of the FGM. Silicon dioxide accounts for uniform particulate dispersion and improved mechanical properties of the FGM [34].

| Material                  | Rubber ash |
|---------------------------|------------|
| Carbon Dioxide, CO$_2$ (%)| 0.10       |
| Sulfur Trioxide SO$_3$ (%)| 16.90      |
| Silicon Dioxide SiO$_2$ (%)| 12.70      |
| Calcium oxide, CaO (%)    | 3.54       |
| Iron (III) Oxide Fe$_3$O$_4$ (%) | 3.18   |
| Aluminium oxide, Al$_2$O$_3$ (%) | 0.51   |
| Potassium oxide, K$_2$O (%) | 0.36      |
| Bromine, Br (%)           | 0.34       |
| Copper (II) Oxide, CuO (%)| 0.21       |
| Chlorine, Cl(%)           | 0.19       |
| Cobalt (II) Oxide, CoO (%)| 0.14       |
| Carbon, C (%)             | —          |
| Titanium Dioxide, TiO$_2$ (%) | —    |
| Zirconium Dioxide, ZrO$_2$ (%) | —    |
| Zinc Oxide, ZnO (%)       | 14.60      |

The addition of rubber ash will enhance the properties of the FG Composite to a large extent. Experimental results with various compositions are given in table 4.

#### Effect of rubber ash concentration on microstructure

The density of the B$_4$C particles (2.52 g cm$^{-3}$) is similar to that of the aluminum alloy (2.7 g cm$^{-3}$), this means that the particle dispersion of the B$_4$C particles to the outer zone of the FGM cylinder is identical to that of the aluminum. The particle dispersion of the FGM cylinder due to the centrifugal force is shown in figure 2. Owing to lower density the rubber ash particles are uniformly distributed throughout the FGM cylinder. It can be concluded from previous works that this type of distribution of Aluminum and B$_4$C is compatible [17, 19, 22]. The addition of rubber ash reinforcements under centrifugal force helps in enhancing the microstructure of the composite [11] as shown in figure 2.

Figure 2 depicts the size of the primary aluminum phase in particle enriched zone, the size of the particles is found to be bigger towards the inner edge of the cylinder (at an average of 120 $\mu$m). The particle size reduced drastically towards the outer edge of the cylinder (at an average of 15–40 $\mu$m) and is shown in figure 2. The reason for the size variation can be attributed to the solidification under centrifugal force. The dendrite arms are broken to form finer structure during solidification, and this can be attributed to shear caused by the movement of ceramic owing to a high weight fraction of B$_4$C particles. The high-weight fraction of B$_4$C particles under
centrifugal force tends to refine the matrix microstructure [18] and introduce fine equiaxed primary phases in the particle depleted zone. The particle sizes in these equiaxed primary phases are generally large, the absence of particles may cause the breaking of dendrites due to cantilever loading and shearing action at the solid-liquid interface [7].

The addition of rubber ash involves adding Sulphur trioxide, zinc oxide, and silicon dioxide particles present in it. Rubber ash is a micromaterial that has an irregular shape, which possesses an advantage, where the irregular shape aids with better binding and workability [35]. Around 42 vol.% B4C is observed near the outer periphery of the cylindrical casting and this reduces gradually as we near the inner periphery. The trend is observed using the image analysis and the results are depicted in figure 3 and table 4. The weight percentage reduces to 39%, 36%, 33%, and 22% as we reach a distance of 1.5 mm, 2 mm, 3 mm, and 4 mm away from the outer periphery, respectively. It can be observed that due to this gradation the specific properties such as hardness, tensile, and specific strength can be enhanced as per the requirements. The centrifugal force applied to the homogenous composite melt of Al (6061)–4% B4C can yield up to a maximum volume fraction of 42% towards the outer edge of the cylinder.

The addition of rubber ash aids with steady dispersion of particles under the centrifugal force, this is due to the reduced density of the rubber ash particles. It can be noted that the dispersion of the rubber ash particles from the inner zone to the outer zone is almost steady, unlike the Boron Carbide particles. The weight percentages for the rubber ash dispersion are 17%, 21%, 19.5%, 20%, 19.5%, 19.5%, 15%, 13% and 9% for 1.5 mm, 2 mm, 3 mm, 4 mm, 5 mm, 6 mm, 6.5 mm, 8 mm and 9 mm distances from the outer edge of the cylinder respectively. This distribution is responsible for the enhancement of the physical properties of Al-B4C-Rubber Ash FGM.

**Effect of rubber ash concentration on the hardness**

The rubber ash constitutes SiO2, SO3, and ZnO whose properties are known to enhance the mechanical properties of the FGM. The presence of SiO2 helps in increasing the hardness of the composite [34]. The transfer of load from the softer matrix to the harder rubber ash particulates offers more resistance to plastic deformation. Strengthening of the composites is caused by a few other mechanisms such as resistance to motion of dislocation facilitated by the distribution of hard particles (SiO2, SO3). The thermal expansion (CTE) mismatch of Al and rubber ash particles cause the dislocation formation [36]. These mechanisms were not effective for 3, 6% wt of rubber ash as the inner zone of FGMs rubber ash content had particles agglomerate and cluster formation in the matrix. Few works reported the decrement in hardness that was due to higher porosity, as porosity does not possess any hardness and contributed to overall hardness reduction [37]. The reason for the reduced hardness of the inner zones can be attributed to the fact that the base matrix is much harder than the rubber ash particles that have a lesser concentration in the outer zones [28–30].

The microhardness increases with the increase in Rubber ash content. The hardness test results are shown in figure 4, depict the hardness of the 6061 Al-B4C-Rubber ash FGM. The hardness is observed for the outer zone, the inner zone, and the middle zone. It can be noted that the harness is maximum at the outer zone followed by the middle zone and then the inner zone for any given composition. The hardness also seems to improve with the increase in the wt% of the rubber ash added with B4C maintained at 4% always.

As the graph depicts the maximum hardness obtained was near the outer zone of the cylinder with a value of 77 HV in the Vickers scale. This was obtained for a composition of 15% rubber ash in the mixture. The minimum hardness obtained was at the inner zone of the cylinder for the sample with no rubber ash reinforcement is 28.4 HV. The reason for the increased hardness near the outer zone can be attributed to the
centrifugal force applied to the composite during centrifugal casting. This centrifugal force causes particles to be concentrated in the outer zone.

When the outer zone values are compared it can be noted that the sample with higher wt% volume rubber ash has more hardness. Similar trends can be observed for the inner and middle zones. On comparing the maximum hardness obtained at the outer zones we can see that the least hardness was for the combination with

![Microstructures of Al(6061)-B₄C-Rubber ash FGMCC hollow cylinder fabricated by horizontal centrifugal casting. Numbers are the distances from the outer to inner periphery in mm.](image)

- (a) 1.5 mm
- (b) 2 mm
- (c) 3 mm
- (d) 4 mm
- (e) 5 mm
- (f) 8 mm

*Figure 2. Microstructures of Al(6061)-B₄C-Rubber ash FGMCC hollow cylinder fabricated by horizontal centrifugal casting. Numbers are the distances from the outer to inner periphery in mm. (a) 1.5 mm; (b) 2 mm; (c) 3 mm; (d) 4 mm; (e) 5 mm; (f) 8 mm.*
0% rubber ash at around 44.6 HV and the hardness value was the most for the combination with 0% rubber at 57.4. The addition of 15 wt% rubber ash seems to have an enhanced hardness of around 25% when compared to FGM with 0 wt% rubber ash. For the middle zone, the maximum hardness values obtained for the FGM with 15 wt% volume rubber ash was 33% more than the hardness value obtained with 0% rubber ash. Similar trends were observed for the inner zone, where the sample 15 wt% rubber ash exhibited 4% more hardness than the sample with 0% rubber ash. The observation concurs with previous works that recommend using industrial wastes as reinforcement materials [28–30].

Effect of rubber ash concentration on tensile strength
Figure 5 shows the change in tensile Strength of FGMMCs as the weight concentration of the Micron rubber ash concentration is varied between 3% to 15% of the overall weight while the weight of Micron B4C is maintained constant at 4%. The tensile strength increases with increasing weight percent of reinforcements as shown in figure 4, the tensile strength of FGM composites are higher than the tensile strength of aluminum alloy without reinforcements. The increased tensile strength is due to the grain refinement and strong multidirectional thermal stress at the Al/B4C/rubber ash interface [23, 24]. The B4C particles act as the heterogeneous nucleation catalyst for aluminum [38, 39] during solidification, due to the increasing weight percent of hard particles, causing a grain-refined strengthening effect. The use of SO3 and ZnO microparticles tend to improve the strength of the rubber. The addition of zinc oxide exhibits the proper distribution of the particles and hence increases the tensile strength of the FGM. The samples are tested by UTM under ASTM standards and the observations are shown in figure 5 and table 4. From the figure, it is evident that the tensile strength is highest for the sample with 15wt% of rubber ash at 198 MPa when compared to other samples. The sample with 0% wt of rubber ash has the least tensile strength at 142.2 MPa. The addition of 15% wt of rubber ash results in a more than 27% increase in tensile strength when compared to the sample with 0% wt of rubber ash. B4C is an attractive reinforcement for aluminum and its alloys showing many of the mechanical and physical properties required of an effective reinforcement, in particular high stiffness and hardness. Additionally, the mechanical
properties of the composites are improved by the presence of Zr \[40, 41\], which helps in the bonding of the particles effectively.

The trend suggests that the tensile strength increased with the increase in %wt of rubber ash, where the tensile strength was observed to be 152 MPa, 168 MPa, 178 MPa, and 192 MPa for 3, 6, 9, and 12% wt of rubber ash respectively. The increase in strength can be attributed to the effective load transfer of the ZnO particles and the proper dispersion of the particles in the matrix \[42\]. The increased tensile strength can also be attributed to the interfacial interaction between the reinforcements and the Al-B\(_4\)C Matrix. This interaction facilitates effective load transfer to be the reinforcements that reduce crack formation. Besides, the presence of SO\(_3\) facilitates better bonding of the particles and hence effectively enhances the stability of the composites \[43\].

**Effect of rubber ash concentration on density**

The density and overall weight of the FGM is reduced greatly due to the addition of rubber ash. Usually, ceramic materials are added as reinforcements for the Al-B\(_4\)C based FGM, but the use of rubber ash instead of ceramic has a huge advantage in terms of weight as the density of rubber ash is almost one-fourth of that of Aluminum. The constituents of the rubber ash are micromaterials that are small in size and irregular in shape. This results in lower weight but enhanced adhesion between the particles to exhibit better weight to strength ratio. The major constituents of rubber ash are SiO\(_2\), SO\(_3\), and ZnO which posses' low density and strong physical properties.

Figure 6 shows the density of the FGM with respect to the weight percentage of rubber ash added. The first sample that was considered had 0% of rubber ash and was the densest sample with nearly 2673 Kg m\(^{-3}\) density. The density seemed to reduce as the % weight of rubber ash increases, this was also observed in previous research works that used fly ash as reinforcement materials \[26, 27\]. The sample with a 15% weight of rubber ash was the least dense with a density of around 2342 Kg m\(^{-3}\). The densities of 3%, 6%, 9% and 12% wt of rubber ash were 2612 Kg m\(^{-3}\), 2551 Kg m\(^{-3}\), 2490 Kg m\(^{-3}\) and 2429 Kg m\(^{-3}\) respectively. The sample with 15% weight of rubber ash was around 13% less dense than the sample with 0% weight of rubber ash.
Effect of rubber ash concentration on specific strength

The specific strength of the sample determines the strength with respect to density. This strength to density plot is illustrated in figure 7. Specific strength is a very crucial factor in determining the effectiveness of the FGM. In most cases, the purpose of using FGM is having high strength combined with low weight. From the figure, it can be noted that the sample with 0% weight of rubber ash has the least specific strength at 53.2 kN-m kg\(^{-1}\). The sample with 15% weight of rubber ash has the highest specific strength of 84.9 kN-m kg\(^{-1}\). The specific strength seems to increase with the increase in the % weight of rubber ash. The reason being, despite the reduced density of rubber ash their tensile strength is strong due to the proper bonding of the rubber ash particles. These particles are micromaterials and are irregularly shaped and owing to the adhesive nature of silicon the bonding between SiO\(_2\), SO\(_3\) and ZnO are strong [44]. This reduced density combined with good strength accounts for enhanced specific strength. The specific strength of 3, 6, 9 and 12% Volume fraction of rubber ash are 58 kN-m kg\(^{-1}\), 66 kN-m kg\(^{-1}\), 71 kN-m kg\(^{-1}\) and 79 kN-m kg\(^{-1}\) respectively. The specific strength of the sample with 15% weight of rubber ash was around 60% more than the sample with 0% weight of rubber ash. The specific strength is given by the following expression

\[
\text{Specific strength} = \frac{\text{Tensile strength (MPa)}}{\text{Density (g cm}^{-3}\text{)}}
\]

Conclusion

This work has initiated economical and lightweight rubber ash as an alternative to ceramic particles being used as reinforcements to aluminum FGM. The outcome of the microstructure analysis using SEM depicted that the distributions of the rubber ash microparticles are even and uniform. The distribution is found to be across all the three zones of the cylinder (Inner Zone, Middle Zone, and Outer Zone) unlike the distribution of boron carbide which was concentrated more towards the outer zone. 15%wt volume fraction of rubber ash composite is having better hardness, more tensile strength (198.09 MPa), less density (2.342 g cm\(^{-3}\)), and more specific strength (84.6 kN-m kg\(^{-1}\)) than a composite with 0%wt, volume fraction of rubber ash. That gives us more hardness, tensile strength, and specific strength with less weight. The FGM with rubber ash reinforcement displayed overall enhanced mechanical and physical properties, making rubber as a viable lightweight, low-cost reinforcement for FGM.

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References

[1] Kumara S and Bharjb R S 2018 Emerging composite material use in current electric vehicle: a review Materials Today: Proceedings 5 27946–54
[2] Frost S and Sullivan A 2009 Global analysis of weight reduction strategies of major OEMs Market Engineering Research
[3] Mavhunga S T, Akinlabi E T, Onitiri M A and Varachia F M 2017 Aluminium matrix composites for industrial use: advances and trends Procedia Manufacturing 7 178–82
Mater. Res. Express 7 (2020) 096522

Nurunabo F, Masu L and Kirabira J B 2019 Novel application of aluminium metal matrix composite Aluminium Alloys and Composites (London: IntechOpen)

Miyamoto Y, Kayser W A, Rabin B H, Kawasaki A and Ford R G 1999 Functionally Graded Materials: Design, Processing and Applications. Materials Technology Series (US: Springer)

Radhika N and Raghu R 2016 Development of functionally graded aluminium composites using centrifugal casting and influence of reinforcements on mechanical and wear properties Trans. Nonferrous Met. Soc. China 26 905–16

El-Gaby I and Saleh B 2019 Functionally graded materials classifications and development trends from industrial point of view SN Appl. Sci. 1 1–23

Ebbottas W S, Akhil S K and Inamboo F L 2016 Centrifugal casting technique baseline knowledge, applications, and processing parameters: overview Int. J. Mater. Res. (formerly Z. Metallkd.) 107 960–9

Rajan T P D, Pillai R M and Pai B C 2010 Characterization of centrifugal cast functionally graded aluminium-silicon carbide metal matrix composites Material Characterization 61 923–8

Perviaz M, Panthapulakkal S, Birat K C, Sain M and Tjong J 2016 Emerging trends in automotive lightweighting through novel composite materials Materials Sciences and Applications 7 26–38

Manikandan R and Arjunan T V 2020 Mechanical and tribological behaviours of aluminium hybrid composites reinforced by CDA-B4C Mater. Res. Express 7 1–17

Rajama T P D and Pai B C 2011 Processing of functionally graded aluminium matrix composites by centrifugal casting technique Mater. Sci. Forum Vol. 690 157–61

Gawali Shivaji V and Tungikar Vinod B 2013 Study of behavioral pattern in wear applications composite in presence of different geometric shapes Sastech Journal 12 15–9

Srivastava A, Garg P, Kumar A, Krishna Y and Varshney K K 2014 A review on fabrication & characterization of hybrid aluminum metal matrix composite International Journal of Advance Research and Innovation 1 242–6

Miracle D B 2005 Metal matrix composites—from science to technological significance Composite Science and Technology 65 2526–40

Lilje T M 2005 Enhancing ductility of Al6061 + 10 wt% B4C through equal-channel angular extrusion processing Mater. Sci. Eng. A 410–411 443–52

Nai S M L, Gupta M and Lim C Y H 2004 Synthesis and wear of Al based, free standing functionally gradient materials: effects of different reinforcement Material Science and Technology 20 577–67

Rao A G, Katkar V A and Shah A K 2010 Fabrication and characterization of aluminum (6061)-boron-carbide functionally gradient material Mater. Manuf. Processes 25 572–6

Watanabe Y, Kawamoto A and Matsuda K 2002 Particle size distributions in functionally graded materials fabricated by the centrifugal solid-particle method Composite Science and Technology 62 861–8

Melgarejo Z H, Suarez O M and Sridharan K 2006 Wear resistance of functionally-graded aluminum matrix composite Scripta Materialia 55 93–8

Duque N B, Melgarejo Z H and Suarez O M 2005 Functionally graded aluminum matrix composites produced by centrifugal casting Mater. Charact. 55 167–71

Kelly A M, Reiswig R D, Hill M A and Blumenthal W R 1994 Preparation of B4C/Al composites for image analysis Mater. Charact. 32 35–9

Kennedy A R and Brampton B 2001 The reactive wetting and incorporation of B4C particles into molten aluminum Scripta Materialia 44 1077–1082

Kennedy A R 2002 The microstructure and mechanical properties of Al–Si–B4C metal matrix composites Journal of Material Science 37 117–23

Prasada S and Shoba C 2015 Experimental evaluation onto the damping behavior of Al/SiC/RHA hybrid composites J. Mater Res. Technol. 17B 1–8

Shaikh M B N, Shaikh M A N, Ahmed M, Nat A and Ali M 2018 Evaluation of the microstructural, mechanical and tribological behaviour of fly ash reinforced aluminium metal matrix composites Materials Focus 7 1–8

Shaikh M B N, Arif S and Arif Siddiqui M 2018 Fabrication and characterization of aluminium hybrid composites reinforced with fly ash and silicon carbide through powder metallurgy Mater. Res. Express 5 1–21

Shaikh M B N, Arif S, Aziz T, Waseem A, Shaikh M A N and Ali M 2019 Microstructural, mechanical and tribological behaviour of powder metallurgy processed SiC and RHA reinforced Al-based composites Surfaces and Interfaces 15 166–79

Alaneme a b, K K and Sanusi K O 2015 Microstructural characteristics, mechanical and wear behaviour of aluminium matrix hybrid composites reinforced with alumina, rice husk ash and graphite Engineering Science and Technology, an International Journal 18 416–22

 SARAVANAN S, Senthilkumar M and Shankar S 2013 effect of particle size on tribological behavior of rice husk ash–reinforced aluminium alloy (AISI10Mg) matrix composites Tribol. Trans. 56 1156–67

Senin1 MS and Shahidian A 2013 Analysis of physical properties and mineralogical of pyrolysis tires rubber ash compared natural sand in concrete material J. Mater. Sci. Eng. 160 012053

Garcia-Sanoguera D, Lopez J and Balart B 2007 Composites based on sintering rice husk–waste tire rubber mixtures Mater. Des. 28 2234–8

Bhoi N K, Singh H and Pratap S 2020 Synthesis and characterization of zinc oxide reinforced aluminum metal matrix composite produced by microwave sintering J. Compos. Mater. 56 91–12

Zayed, I S M, Alshimy, I A M and Fahmy A E 2014 Effect of surface treated silicon dioxide nanoparticles on some mechanical properties of maxillofacial silicone elastomer International Journal of Biomaterials 2014 1–7

Senin S, Shahidian S and Leman A S 2016 Analysis of physical properties and mineralogical of pyrolysis tires rubber ash compared natural sand in concrete material Materials Science and Engineering 160 1–10

Siva D, Shoba C and Ramanaiah N 2013 Investigations on mechanical properties of aluminum hybrid composites Integr. Med. Res. 31 79–85

Gladston J A K, Sherif N M, Dinahan I, Selvam J D R and Raja Selvam J M 2015 Production and characterization of rich asphaltic particulate reinforced Al6061 aluminum alloy composites by compocasting Trans. Nonferrous Met. Soc. China 25 683–91

Mazahery A, Abdizadeh H and Baharvandi H R 2009 Development of high-performance A356/nano-Al2O3 composites Journal of Material Science Engineering 518 61–4

Briaf M C and Cline T W 1992 The use of single fibre pushout testing to explore interfacial mechanics in SiC monofilament-reinforced TiAl A photostatic study of the test Journal of Acta Metallurgia Materials 40 131–9

Gode C 2013 Mechanical properties of hot pressed SiCp and B4Cp/alumix 123 composites alloyed with minor Zr Strömeyer Composites 54 34–40
[41] Qin J 2016 Mechanical Properties and Hot Workability of Al-15% B 4 C Metal Matrix Composites with Sc and Zr for Elevated Temperature Applications (Canada: Université du Québec à Chicoutimi)

[42] Thipperudrappa S, Kini A U and Hiremath A 2020 Influence of zinc oxide nanoparticles on the mechanical and thermal responses of glass fiber-reinforced epoxynanocomposites Polym. Compos. 41 174–81

[43] Horkoss S, Escadeillas G, Rizk T and Lteif R 2016 The effect of the source of cement SO 3 on the expansion of mortars Case Studies in Construction Materials 4 62–72

[44] He X, Rodrigues A M and Zhang R 2017 Reinforcement of the mechanical properties in nitrile rubber by adding graphene oxide/silicon dioxide hybrid nanoparticles J. Appl. Polym. Sci. 46091 1–8