



## Review Article

# Aluminium matrix hybrid composites: a review of reinforcement philosophies; mechanical, corrosion and tribological characteristics



Michael Oluwatosin Bodunrin<sup>a,b,\*</sup>, Kenneth Kanayo Alaneme<sup>a,c</sup>, Lesley Heath Chown<sup>b</sup>

<sup>a</sup> Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, Nigeria

<sup>b</sup> School of Chemical and Metallurgical Engineering, DST-NRF Centre of Excellence in Strong Materials, African Materials Science and Engineering Network (AMSEN), University of The Witwatersrand, Johannesburg, South Africa

<sup>c</sup> Department of Mining and Metallurgical Engineering, Ongwediva Engineering Faculty Campus, University of Namibia, Ongwediva, Namibia

### ARTICLE INFO

#### Article history:

Received 6 September 2014

Accepted 5 May 2015

Available online 9 June 2015

#### Keywords:

Agro waste

Synthetic reinforcement

Fly ash

Industrial wastes

MMCs

### ABSTRACT

Aluminium hybrid composites are a new generation of metal matrix composites that have the potentials of satisfying the recent demands of advanced engineering applications. These demands are met due to improved mechanical properties, amenability to conventional processing technique and possibility of reducing production cost of aluminium hybrid composites. The performance of these materials is mostly dependent on selecting the right combination of reinforcing materials since some of the processing parameters are associated with the reinforcing particulates. A few combinations of reinforcing particulates have been conceptualized in the design of aluminium hybrid composites. This paper attempts to review the different combination of reinforcing materials used in the processing of hybrid aluminium matrix composites and how it affects the mechanical, corrosion and wear performance of the materials. The major techniques for fabricating these materials are briefly discussed and research areas for further improvement on aluminium hybrid composites are suggested.

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\* Corresponding author.

E-mail: [mic.tosin@live.com](mailto:mic.tosin@live.com) (M.O. Bodunrin).

<http://dx.doi.org/10.1016/j.jmrt.2015.05.003>

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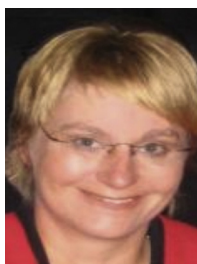


**Engr. M.O. Bodunrin** is a lecturer II in the Department of Metallurgical and Materials Engineering, Federal University of Technology Akure. He is a registered engineer with Council for Regulation of Engineering in Nigeria (COREN) and currently a PhD research student at the School of Chemical and Metallurgical Engineering, University of Witwatersrand, Johannesburg, South Africa.



**Dr. K.K. Alaneme** is a senior lecturer in the Department of Metallurgical and Materials Engineering, Federal University of Technology Akure. He is currently a visiting Senior Lecturer in the Department of Mining and Metallurgical Engineering, University of Namibia, Ongwediva Engineering Faculty Campus, Namibia. He has successfully supervised several Doctoral and Masters Students. His research

interests include metallurgical equipment design; phase transformation and materials synthesis and characterization with emphasis on the mechanical, corrosion and wear performance of metal matrix composites, shape memory alloys, dual phase steels among others.



**Dr. L.H. Chown** is a senior lecturer in the School of Chemical and Metallurgical Engineering, University of Witwatersrand. She is one of the two focus area coordinators of strong metallic alloys under the DST-NRF Centre of Excellence in Strong materials, University of Witwatersrand. She has successfully supervised several Doctoral and Masters Students. Her research interest includes Structure – property relationships in metallic alloys:

titanium, steel, platinum; Gleeble process simulation, continuous casting, hot working and cold forming; thermodynamic modelling (Thermo-Calc); powder metallurgy among others.

sports and recreation industries [6]. MMCs are basically metallic alloys reinforced with mostly ceramic materials. The common metallic alloys utilized are alloys of light metals (Al, Mg and Ti) however, other metallic alloys like zinc (Zn), copper (Cu) and stainless steel have been used [7,8]. Aluminium remains the most utilized metallic alloy as matrix material in the development of MMCs and the reasons for this has been reported [6,9,10]. Likewise, the merits of using discontinuous ceramic particulates or whiskers over continuous ceramic fibres for producing aluminium matrix composites (AMCs) are available in literatures [4,5,11]. However, high cost and limited supply of conventional ceramic reinforcing materials especially in developing countries has remain a major problem associated with the development of discontinuously reinforced aluminium matrix composites (DRAMCs) [12]. Other challenges facing DRAMCs that are reported to be of interest to researchers are inferior ductility, low fracture toughness and inability to predict the corrosion behaviour of AMCs [5,13].

Research efforts put in place to resolve these problems are mostly channelled towards selecting the right choice of reinforcing materials. This is an indication that the reinforcing materials play significant role in determining the overall performance of the composites. Considering the number of published articles surveyed while preparing this review, it was observed that three different approaches have been adopted to improve the performance of DRAMCs. The first approach involves finding alternative and cheaper reinforcements in the development of DRAMCs. This is aimed at providing solution to problems posed by high cost and limited availability of conventional ceramic reinforcements [14–17]. Industrial wastes and agro waste derivatives are some of the alternative reinforcing materials that have been investigated [15,17,18]. The results obtained from the investigations carried out on these alternative reinforcements have been promising as they show significant improvement in the properties of the composites developed over the unreinforced alloy. However, they possess inferior properties when compared to the DRAMCs developed using conventional synthetic reinforcements [19,20].

The second approach is aimed at optimizing the properties of DRAMCs by reducing the particle size of synthetic ceramic materials from micron scale to nano scale (usually from  $<50\ \mu\text{m}$  to an average of  $<100\ \text{nm}$ ) [7,21–23]. The fracture toughness and ductility of DRAMCs have reportedly been improved without significant drop in strength when nanoparticles are used as reinforcing materials [1,7,24–26]. This development seem to be an interesting one however, high cost and availability of nano-particulates seem to be a limiting factor especially in developing countries where AMCs are produced. Also, there is still inconclusive evidence to substantiate the mechanisms of ductility and fracture toughness improvement in nano-particulate reinforced composites. Some authors have reported improved strength and wear resistance at the expense of ductility [24,26].

The third approach involves the development of DRAMCs using two or more reinforcing materials. This class of DRAMCs is called hybrid composites. This approach gives room for possible reduction of cost coupled with property optimization in DRAMCs. Some authors have reported comparable or improved performance of hybrid AMCs over single reinforced

## 1. Introduction

Current engineering applications require materials that are stronger, lighter and less expensive. A good example is the current interest in the development of materials that have good strength to weight ratio suitable for automobile applications where fuel economy with improved engine performance are becoming more critical [1]. In-service performance demands for many modern engineering systems require materials with broad spectrum of properties, which are quite difficult to meet using monolithic material systems [2]. Metal matrix composites (MMCs) have been noted to offer such tailored property combinations required in a wide range of engineering applications [1,2]. Some of these property combinations include: high specific strength, low coefficient thermal expansion and high thermal resistance, good damping capacities, superior wear resistance, high specific stiffness and satisfactory levels of corrosion resistance [3–5].

MMCs are fast replacing conventional metallic alloys in so many applications as their use have been extended from predominantly aerospace and automobile to defence, marine,

AMCs even at reduced processing cost [2,27]. This has put hybrid reinforced AMCs under the spotlight as many researchers forecast the huge promise of developing high performance – low cost MMCs through this route. This article attempt to review the studies conducted on the different combination of reinforcing particulates used in the development of hybrid AMCs and how it influences the overall performance of the composites.

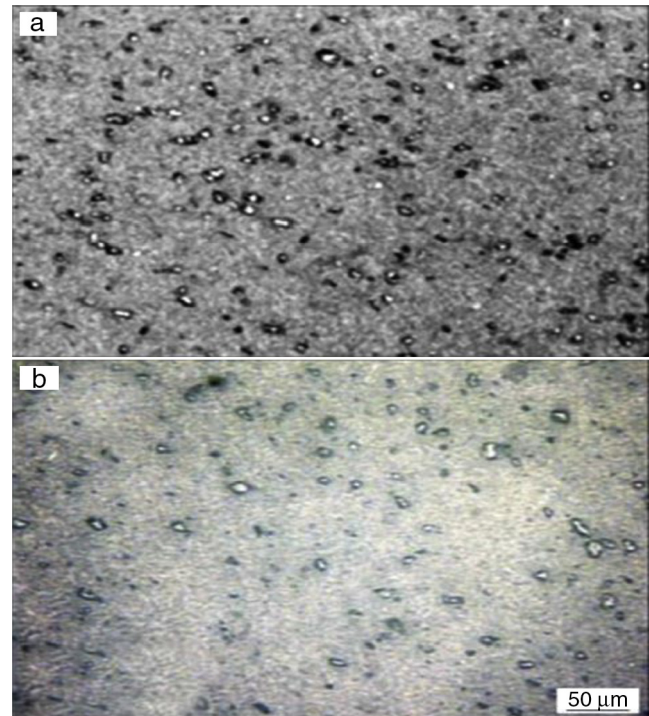
## 2. Reinforcing materials in AMCs

The different reinforcing materials used in the development of AMCs can be classified into three broad groups, which are synthetic ceramic particulates, industrial wastes and agro waste derivatives. The final properties of the hybrid reinforcement depend on individual properties of the reinforcement selected and the matrix alloy [10,28,29]. Moreover, the processing route adopted for synthesizing AMCs depends on the nature of the matrix alloy and reinforcing materials which also influence the final properties of AMCs [7,9,29,30]. This is because most of the parameters put into consideration during the design of AMCs are linked with the reinforcing materials. A few of such parameters are reinforcement type, size, shape, modulus of elasticity, hardness, distribution in the matrix among others [6]. Based on the published articles studied, the discussion on the combinations of reinforcement used in the synthesis of hybrid AMCs is divided into three broad groups. These are hybrid AMCs with two synthetic ceramic materials; an agro-waste derivative combined with synthetic ceramic materials; and industrial waste combined with synthetic reinforcement.

## 3. Hybrid AMCs with two different synthetic ceramic materials

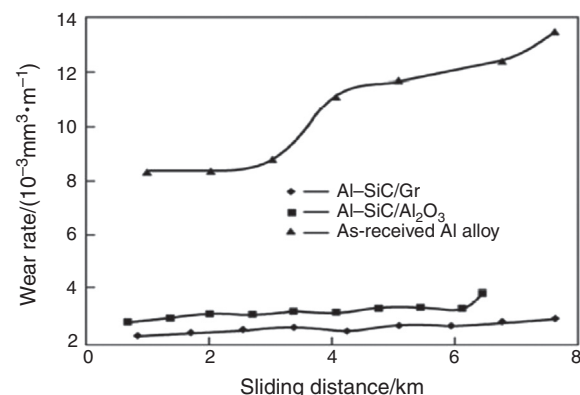
This category of hybrid AMCs is developed basically for performance optimization with less consideration on the production cost. Silicon carbide (SiC), alumina ( $\text{Al}_2\text{O}_3$ ), boron carbide ( $\text{B}_4\text{C}$ ), tungsten carbide (WC), graphite (Gr), carbon nanotubes (CNT) and silica ( $\text{SiO}_2$ ) are some of the synthetic ceramic particulate that has been studied but silicon carbide and alumina are mostly utilized compared to other synthetic reinforcing particulates [11]. Conventional AMCs reinforced with SiC or  $\text{Al}_2\text{O}_3$  have shown improved strength and specific stiffness over the monolithic alloys but this occurs at the expense of ductility and fracture toughness [10,13,28]. Ductility and fracture toughness are important material properties that are necessary for preventing failures under in-service stress or shock load applications. As mentioned earlier, corrosion performance of these AMCs are also not consistent judging from reports published in the past [30,31]. These have necessitated the use of two or more synthetic reinforcing particulates for property optimization. Graphite and Boron carbide have been used alongside with SiC or  $\text{Al}_2\text{O}_3$  to optimize the performance of AMCs. Some of the findings in recent published articles are presented below.

Deravaju et al. [32] studied the influence of SiC/Gr and SiC/ $\text{Al}_2\text{O}_3$  on the wear properties of friction stir processed Al 6061-T6 hybrid composites. The authors reported uniform



**Fig. 1 – Microstructure of surface hybrid composites (a) Al-SiC/Gr; (b) Al-SiC/ $\text{Al}_2\text{O}_3$  after Deravaju et al. [32] with permission from Elsevier.**

distribution of the reinforcing materials in the nugget zone of the hybrid AMCs as shown in Fig. 1. Similar report has been made by the authors on hybrid AMCs containing SiC and  $\text{Al}_2\text{O}_3$  [33]. The hardness and wear resistance of the hybrid composites were superior to that of the matrix material. Furthermore, hardness of the composites containing SiC and  $\text{Al}_2\text{O}_3$  was higher than that of the composites with SiC and Gr due to the combined pinning effect of SiC and  $\text{Al}_2\text{O}_3$  and the higher hardness of  $\text{Al}_2\text{O}_3$  to that of the Gr. However, composite containing  $\text{Al}_2\text{O}_3$  despite its hardness has inferior wear resistance to that of the composites containing Gr (as shown in Fig. 2) because Gr exhibits higher solid lubricating effect than  $\text{Al}_2\text{O}_3$ .



**Fig. 2 – change in wear rate with sliding distance of Al-SiC/Gr and Al-SiC/ $\text{Al}_2\text{O}_3$  surface hybrid composite after Deravaju et al. [32] with permission from Elsevier.**

The improved wear resistance of the hybrid composites over the unreinforced alloys was attributed to the load bearing capacity of the SiC carbide and the solid lubricating effect of Gr and Al<sub>2</sub>O<sub>3</sub>. Al<sub>2</sub>O<sub>3</sub> was reported to have solid lubricating effect due to the similar hexagonal closed packed structure it has with boron nitride (BN), a good solid lubricant like graphite [34,35].

Rajmohan et al. [36] studied the influence of mica on the mechanical and wear properties of aluminium matrix composites reinforced with 10 wt% silicon carbide. The percentage of mica added to the 10 wt% SiC reinforced Aluminium composites was 6% in step of 3. It was reported that hybrid composites containing mica and SiC as reinforcements have superior hardness, tensile strength and wear resistance than the single reinforced silicon carbide aluminium composites. The superior wear resistance observed was ascribed to the formation of a stable mechanically mixed layer (MML) formed on the composites which reduces the wear loss. The hybrid composites with 3 wt% mica have the highest wear resistance, strength and hardness. These properties dropped as the mica content was increased to 6 wt%. The reason for this was not reported and still need further studies.

Ramnath et al. [37], evaluated the mechanical properties of aluminium hybrid composites reinforced with Al<sub>2</sub>O<sub>3</sub> and B<sub>4</sub>C. B<sub>4</sub>C was considered despite its high cost because of its high strength, low density, extremely high hardness, good chemical stability and neutron absorption characteristics. The hybrid composites exhibited superior hardness and impact strength than the unreinforced alloy. However, the unreinforced alloy had slightly higher tensile strength and superior flexural properties than the hybrid counterparts. Microstructural analysis revealed poor stirring and uneven distribution of the reinforcements in the matrix was responsible for this observation. Ravindran et al. [38] investigated the microstructure and mechanical properties of aluminium hybrid nano-composites with the addition of graphite as a solid lubricant. The composites had 5 wt% SiC with varied graphite content up to 10 wt%. It was reported that tensile strength, wear resistance and hardness increased with increasing reinforcement. The hybrid composites had superior mechanical properties than the single reinforced Al/5 wt% SiC composite with Al/5 wt% SiC/10 wt% Gr. having the highest strength and wear resistance.

A number of review papers on the mechanical behaviour, machining and tribological properties of aluminium hybrid composites reinforced with two different synthetic ceramic materials have been reported by some authors [25,39-41]. The authors concluded that the reinforcing materials have significant effect on the improvement of the tensile strength, hardness machinability and tribological properties of the composites. This was ascribed to the load bearing capacities and pinning effect of the hard ceramic particulates and the solid lubricating effect possess by selected reinforcement such as graphite, alumina and boron nitride. It is however worth mentioning that there is no information yet on the influence of double synthetic ceramic reinforcement on the corrosion behaviour of aluminium hybrid composites judging from articles published in this area in the past. In addition, most of the articles available on double synthetic reinforced hybrid composites compared the mechanical properties obtained with

unreinforced alloy rather than the single reinforced composites, therefore, further investigation should be carried out to determine how much the mechanical properties are improved when comparing the hybrid composites with double synthetic reinforcement to single reinforced composites. This will serve as a basis for determining optimum processing parameters in line with production cost.

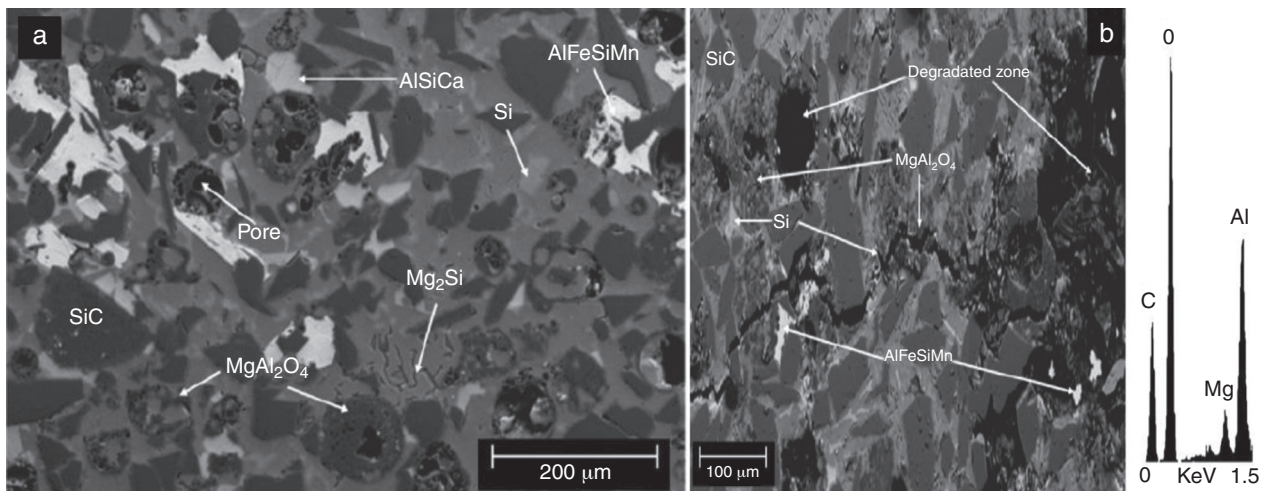
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#### 4. Hybrid AMCs with synthetic and industrial waste reinforcement

Fly Ash (FA) and Red Mud are typical industrial waste gotten from the power plant and aluminium industry respectively [17,42]. These wastes have been suggested to be suitable for use as reinforcing materials in AMCs. Although research work reporting the use of red mud as reinforcement in MMCs are sparse, extensive studies have been carried out on the use of fly ash as reinforcement in both single and hybrid composites [17,43]. Fly ash is a by product of coal combustion and is readily available in many industrialized nations such as USA, United Kingdom, Canada, China among others. About 5 million tonnes of fly ash is produced in Canada annually [43]. Fly ash produced in Canada are of two types which include class F obtained by burning of bituminous coal and class C obtained by burning of sub-bituminous coal and lignite. Class F is preferred over class C for the synthesis of AMCs due to limited amount of calcium oxide (CaO) in its chemical composition. The preponderant oxides in the FA include Al<sub>2</sub>O<sub>3</sub>, SiO<sub>2</sub>, and Fe<sub>2</sub>O<sub>3</sub> while other oxides that are present in trace amount include K<sub>2</sub>O, NaO and MgO. The preponderant oxides make FA suitable for use in synthesis of AMCs. Moreover low density and low cost are other attractive benefits of FA [43].

There have been discrepancies in the results published on the influence of FA on the mechanical properties of MMCs. Rohatgi et al. [44] reported slight improvement in hardness, tensile properties and wear resistance of FA reinforced AZ91D based composites while Gikonoo et al. [43] found that using FA as reinforcing materials in cast alloy A535 based composites reduced the tensile strength and hardness of the composites due to segregation and particle clustering of the FA in the aluminium matrix. Anikumar et al. [17] in contrast to the findings of Gikonoo et al. [43] reported that increased tensile strength, compressive strength and hardness was obtained by increasing weight fraction of FA up to 15% in Al(6061) based composites. Although uniform distribution of the FA was obtained in the aluminium matrix, the ductility decreased with increase in weight fraction of FA. An increase in particle size of FA reduced the strength (tensile and compressive) and hardness of the resulting composites. It is reasonable to conclude that, like the synthetic ceramic particles, improved hardness and tensile strength is obtainable when FA is evenly dispersed without clustering or segregation in the aluminium matrix.

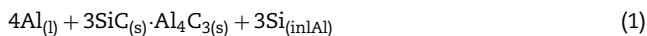
Apart from the influence of FA on hardness, tensile and compressive strengths, several other authors have reported that FA improves the wear resistance and machinability of AMC composites due to the solid lubricating effect it possesses, low cost and low density. Consequently, FA has been used as a complementing reinforcement to synthetic ceramic



**Fig. 3 – (a and b) SEM photomicrograph of composite specimens obtained at 1150 °C for 70 min. (a) Shortly after processing, (b) after exposure to ambient atmosphere for 1 month after [48] with permission from Elsevier.**

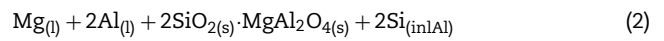
particulates in the development of hybrid AMCs. Prasat and Subramanian [45] studied the tribological properties of AlSi10Mg/fly ash/graphite hybrid metal matrix composite. They found that the tensile strength, hardness and wear resistance were higher in the hybrid composite compared to unreinforced alloy and alumina–graphite composites. The improved wear resistance was attributed to load bearing capacities of FA and the lubricating effect of graphite; wear rate was also observed to reduce with increase in FA content.

Moorthy et al. [46] studied the dry sliding wear and mechanical behaviour of Aluminium/Fly ash/Graphite hybrid metal matrix composites using Taguchi method and reported that load was the most influencing factor affecting the wear rate of the composites followed by sliding speed and fly ash content respectively. There was an increase in the hardness of the hybrid composites as fly ash content increases. FA can also be used to suppress interfacial reaction that exists between matrix and the reinforcing particulate. Bobic et al. [31] reported that SiC undergoes interfacial reaction at high temperature during processing of the composites according to the following equation:



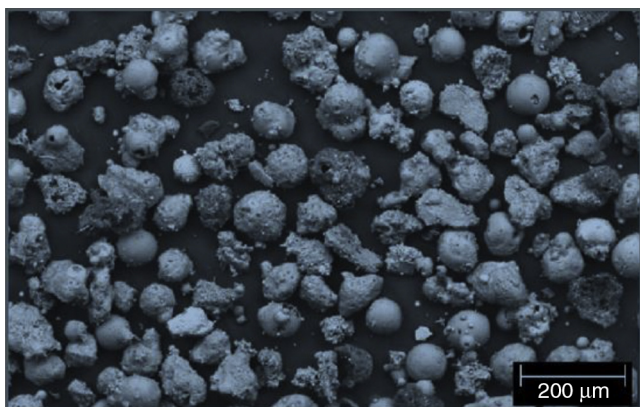
The  $\text{Al}_4\text{C}_3$  phase (aluminium carbide needle phase) is known to have negative influence on the corrosion and mechanical properties of AMCs. David et al. [47] synthesized and characterized aluminium hybrid composites reinforced with SiC and FA via stir casting technique. Tensile strength and hardness of the composites were improved due to high dislocation resulting from thermal mismatch between the reinforcement and the matrix in conjunction with large surface area of the hard ceramic phase, which bears the load transferred by the matrix when subjected to loading conditions. Microstructural evaluation revealed that SiC and FA was uniformly distributed in the aluminium matrix and FA was effective in suppressing the formation of  $\text{Al}_4\text{C}_3$  phase due to presence of  $\text{SiO}_2$  in the FA. Impeding the formation of the  $\text{Al}_4\text{C}_3$  phase by FA has been reported to

improve the corrosion performance of aluminium hybrid composites. Escalera-Lozano et al. [48] evaluated the corrosion characteristics of Al/SiC<sub>p</sub>/MgAl<sub>2</sub>O<sub>4</sub> hybrid composites fabricated with fly ash and recycled aluminium. The MgAl<sub>2</sub>O<sub>4</sub> was formed in situ by the reaction between the  $\text{SiO}_2$  in the fly ash and aluminium alloy matrix according to Eq. (2).



The two types of aluminium alloys used were Al-8Si-15Mg and Al-3Si-15Mg. Mg and Si were added in high amount to improve wettability between the matrix and the reinforcement. The first matrix alloy contained SiC and uncalcined FA while the second matrix was reinforced with SiC and calcined FA. The composites were exposed indoor at ambient atmosphere and average relative humidity of 54%. Composites reinforced with uncalcined FA and SiC corroded within the first one month of exposure. The first feature observed on the corroded sample was pitting followed by the release of white grey powders and finally transgranular and intergranular cracks. The other composites with calcined FA and SiC did not corrode throughout the exposure time. The inferior performance of Al-8Si-15Mg/SiC/MgAl<sub>2</sub>O<sub>4</sub> was ascribed to the formation of electrochemically active MgSi<sub>2</sub> phase, which acted as an active anode and promoted localized corrosion via galvanic coupling as shown in Fig. 3a and b. Microstructural analysis revealed that the uncalcined FA was effective in preventing the formation of the  $\text{Al}_4\text{C}_3$  phase during the production process due to the presence of  $\text{SiO}_2$ . This was affirmed from the XRD pattern, which did not show the degradation of SiC after the composite was produced. However, Fourier transformed infra red spectroscopy (FTIR) revealed that the aluminium carbide phase was formed in the bulk composites due to the reaction between the carbon of the FA and molten aluminium.

The superior performance of the Al-3Si-15Mg/SiC<sub>p</sub>/MgAl<sub>2</sub>O<sub>4</sub> was attributed to the successful prevention of the  $\text{Al}_4\text{C}_3$  phase due to the presence of  $\text{SiO}_2$  in FA and also the absence of carbon in the FA due to calcining



**Fig. 4 – SEM photomicrograph showing the typical morphology of the fly ash after [48] with permission from Elsevier.**

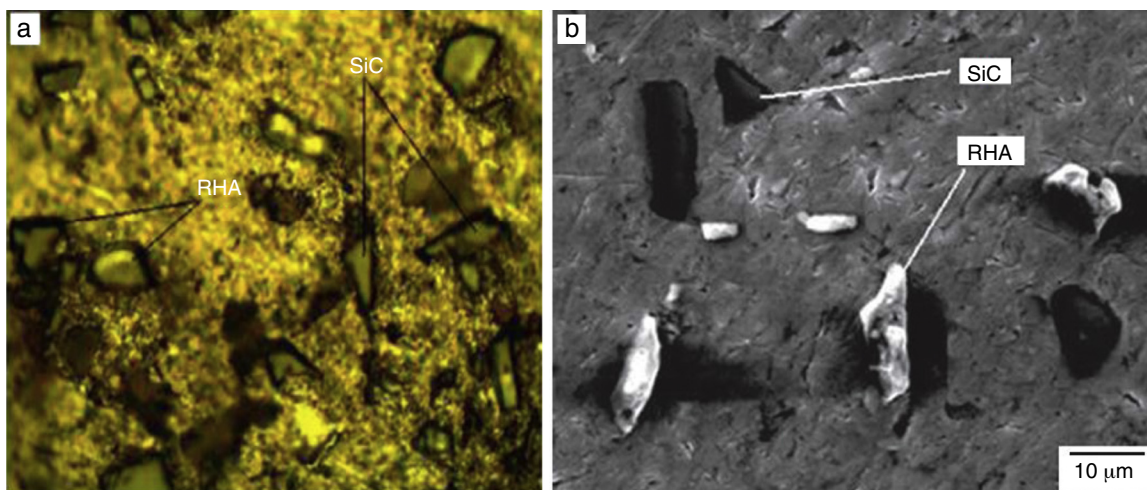
treatment. Moreover, the presence of low silicon in the matrix alloy prevented the formation of  $MgSi_2$  intermetallic phase, which promoted localized galvanic corrosion in the Al-8Si-15Mg/SiCp/MgAl<sub>2</sub>O<sub>4</sub> composites. Reports from Rohatgi et al. [44] and Escalero-Lorenzo et al. [48] suggest using FA with cenosphere morphology promotes the general performance of the resulting composites (Fig. 4).

## 5. Hybrid AMCs with synthetic and agro waste derivatives as reinforcement

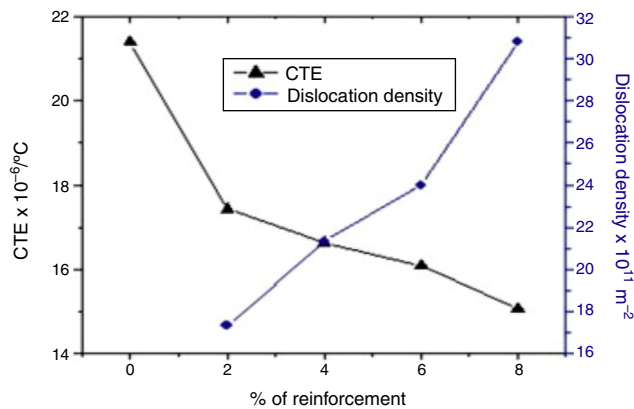
A new generation of hybrid AMCs have been developed using agro waste derivatives as a complementing reinforcement to synthetic reinforcement. The agro waste derivatives offer some advantages when used in the synthesis of AMCs. These advantages include low cost, accessibility, low density, and reduced environmental pollution. A few number of agro waste have been processed into ashes and their suitability for use as reinforcing phase material have been studied [16,19]. Agro waste derivatives are believed to be very promising materials

for the development of AMCs on a commercial scale. This is because there are limited synthetic reinforcing materials available in most developing countries and where these reinforcing materials are available, they are very expensive. Moreover, most developing countries are not as industrialized as developed countries so the use of industrial waste (fly ash) is quite scarce as these wastes are limited. The agro wastes studied in the past for the purpose of using them as reinforcement in AMCs include: bamboo leaf ash (BLA), rice husk ash (RHA), bagasse ash (BA), palm kernel shell ash (PKSA), maize stalk ash (MSA), corn cob ash (CCA), bean shell waste ash (BSWA) just to mention a few [12,14,15,18,19,49]. Prior to the development of hybrid AMCs with agro waste ash serving as complementing reinforcement, single reinforced AMCs have been developed. In general, the agro waste improved the properties of the AMCs over the unreinforced alloy. However, the properties obtained are inferior to that offered by synthetic reinforcement. Research efforts seeking to produce high performance hybrid AMCs where strength levels are maintained at reduced cost informed the fabrication of this class of hybrid AMCs.

An overview of the recent studies on AMCs reinforced with agro waste derivatives and synthetic ceramic particulates is presented below. The fabrication characteristics and mechanical behaviour of rice husk ash–alumina reinforced Al-Mg-Si alloy matrix hybrid composite produced via stir casting was studied by Alaneme et al. [20]. The 10 wt% reinforcing phase consisted of 2, 3, 4, and 6 wt% RHA as a complementing reinforcement to alumina. The authors reported that there was a slight decrease in hardness, ultimate tensile strength of the hybrid composites as compared with the single reinforced Al-Mg-Si/Al<sub>2</sub>O<sub>3</sub> composites. However, composites sample containing 2 wt% exhibited higher specific strength, percentage elongation and fracture toughness than the single reinforced AMCs. The slight reduction in yield strength, ultimate tensile strength and hardness was attributed to lower hardness value of silica, which is the predominant compound in the rice husk ash. In addition, the close modulus of elasticity (60–70 GPa) of SiO<sub>2</sub> to that of aluminium also contributed to reduction in strength. Strengthening mechanism in AMCs have been established and reported by researchers as direct and indirect



**Fig. 5 – (a and b) Optical and scanning electron micrographs of Al 356.2/RHA/SiC composites after [50] with permission from the author.**



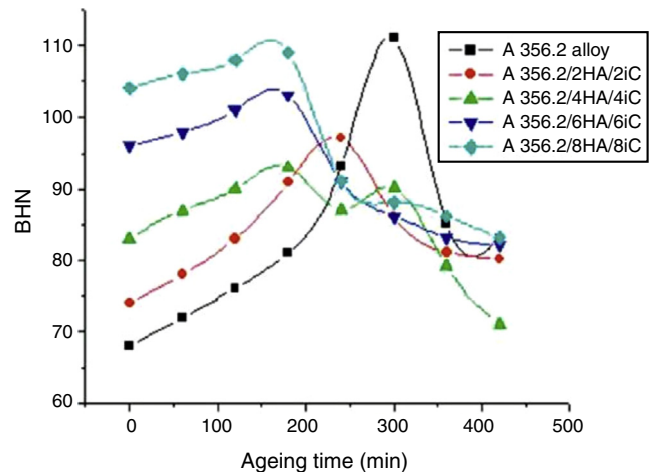
**Fig. 6 – Variation of CTE and dislocation density with % reinforcement reprinted from [50] with permission from the author.**

mechanisms. The direct involves load transfer from the softer matrix to the hard ceramic particulates while the indirect mechanism involves the generation of high dislocation density due to thermal mismatch between the coefficient of thermal expansion (CTE) of the matrix and reinforcement during the production process. Despite the reduction in strength and hardness of the composites, the maximum reduction in strength was less than 11% even when  $\text{Al}_2\text{O}_3$  is replaced by 60% of RHA.

Prasad et al. [50] carried out an investigation on stir cast aluminium hybrid composite containing equal amount of rice husk ash and silicon carbide from 2% to 8% in step of 2. They found out that there was homogenous distribution of the reinforcement in the matrix (Fig. 5). Hardness, yield strength and ultimate tensile strength increased with increase in the reinforcement while percentage elongation and CTE had inverse relationship with increasing reinforcement.

The strengthening mechanism was attributed to thermal mismatch which generated increasing dislocation density as the reinforcing materials increases as shown in Fig. 6. Furthermore, the ageing response of the hybrid composites at  $155^{\circ}\text{C}$  shown in Fig. 7 was faster than the monolithic alloy. The time taken to obtain maximum hardness for the hybrid composites was higher than that of the monolithic alloy due to higher dislocation density of the composites.

Alaneme and Adewale [51] evaluated the mechanical behaviour of Al (6063) hybrid composites reinforced with 5, 7.5 and 10 wt% silicon carbide and RHA. The mix ratios of the RHA in the reinforcing phase are 1:0; 1:3; 1:1; 3:1 and 0:1. It was reported that the tensile strength, yields strength and specific strength of the composites increased with increasing weight percent of the reinforcing phase (RHA + SiC) while the fracture toughness decreased with increasing weight percent of the reinforcing phase. The percentage elongations of the composites were invariant of the reinforcing phase and the RHA content and as a result, the authors acclaimed that the addition of the RHA did not have a negative influence on the ductility of the composites. The increase in strength was ascribed to similar mechanism stated by [50]. The author also revealed that a careful observation of the role of RHA on the mechanical properties of the composites

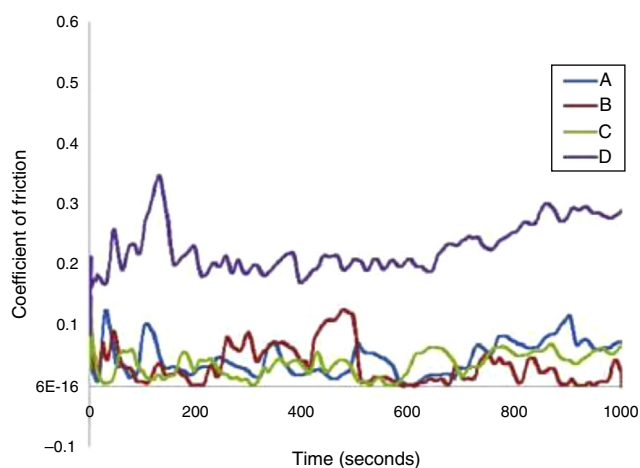


**Fig. 7 – Plot of Brinell hardness against ageing time for Al 356.2 alloy and Al356.2/RHA-SiC hybrid composites reprinted from [50] with permission from the author.**

shows that yield strength, ultimate tensile strength and specific strength reduces as the content of RHA in the reinforcing phase increases. This was attributed to the lower hardness and elastic modulus of silica present in the RHA as compared with the hardness of the silicon carbide. Despite the reduction in strength, the percentage reduction of the specific strength was quite low when compared with yield strength and UTS. Also, sample with reinforcement mix ratio of 1:3 (RHA:SiC) was reported to have very close values to that of the single reinforced Al-Mg-Si/SiC composites. The hybrid composites containing RHA has improved fracture toughness due to reduction in hard SiC particulate in the composites.

Alaneme and Adewuyi [52] investigated the influence of BLA as a complementing reinforcement to  $\text{Al}_2\text{O}_3$  on the mechanical behaviour of Al-Mg-Si based hybrid composite. BLA constitutes 2, 4 and 6 percent of the entire 10 wt% of the reinforcing phase. It was reported that the tensile strength, yield strength and specific strength reduces with increasing BLA in the reinforcing phase. However, the slight reduction was less than 9% even with 40% replacement of  $\text{Al}_2\text{O}_3$  by BLA. This indicates that the introduction of the BLA does not have significant effect on the performance of the hybrid composites. The BLA for certain mix ratios as reported in the case of RHA exhibited improved ductility and resistance to brittle fracture when used as a complimenting reinforcement to synthetic reinforcement ( $\text{Al}_2\text{O}_3$  and SiC). Similar findings have been reported on the tensile strength, specific strength, yield strength and fracture toughness of aluminium hybrid composites containing SiC and BLA. The only exception in this case was an increased ductility as the content of BLA increases in 10% weight of the reinforcing phase [49].

Considering the articles surveyed on hybrid AMCs, it is reasonable to conclude that using agro waste derivatives as a complementing reinforcement in the development of hybrid AMCs can improve the fracture toughness and ductility of AMCs without significant drop in strength. Despite the potentials of agro waste derivatives in cost reduction and maintaining performance levels in terms of mechanical



**Fig. 8 – Variation of coefficient of friction with time for the single reinforced Al-Mg-Si/10 wt%  $\text{Al}_2\text{O}_3$  (A), and hybrid reinforced Al-Mg-Si/BLA-  $\text{Al}_2\text{O}_3$  Al-Mg-Si/2 wt%BLA- 8 wt%  $\text{Al}_2\text{O}_3$  (B), Al-Mg-Si/3 wt%BLA- 7 wt%  $\text{Al}_2\text{O}_3$  (c) and Al-Mg-Si/4 wt%BLA- 6 wt%  $\text{Al}_2\text{O}_3$  (D) composites reprinted from [54] with permission from ESG and the author.**

properties, a few number of researchers were curious about the influence of agro waste derivative reinforcements on the corrosion and wear performance of AMCs when they are used in applications where they are exposed to corrosive and wear attacks. The agro waste derivatives are known to have the potentials of suppressing  $\text{Al}_4\text{C}_3$  phase due to presence of more than 50% silica in their composition just as in the case of fly ash. It was of interest to some researchers to find out if this phenomenon would help achieve improved corrosion resistance in hybrid AMCs reinforced with synthetic and agro waste derivative reinforcements. Alaneme et al. [49] studied the influence of BLA on the corrosion performance of hybrid AMCs reinforced with BLA and SiC using gravimetric analysis. They revealed that the BLA improved corrosion resistance in 3.5% NaCl while the single reinforced Al-Mg-Si/10 wt% SiC had superior corrosion resistance in 0.3M  $\text{H}_2\text{SO}_4$ . Similar observation of inferior corrosion resistance due to RHA was also reported for hybrid Al-Mg-Si/SiC-RHA composites in 3.5 wt% NaCl environment [53]. Preferential dissolution of more anodic Al-Mg-Si matrix at the matrix-reinforcements interfaces was established as the primary corrosion mechanism. For hybrid AMCs comprising RHA/ $\text{Al}_2\text{O}_3$  and BLA/ $\text{Al}_2\text{O}_3$  as the reinforcing phase, the corrosion resistance of the hybrid AMCs reduces with the addition of the agro waste ashes [8,54]. The corrosion mechanism reported was similar to BLA/SiC reported above. Although RHA and BLA can effectively avoid the formation of  $\text{Al}_4\text{C}_3$  phase during the fabrication of hybrid AMCs, the precipitation of  $\text{Mg}_2\text{Si}$  in some cases enhance localized corrosion. In general, for most of the hybrid AMCs, the wear rates are comparable with the single reinforced AMCs (as shown in Fig. 8).

The wear performances of certain mix ratios of the reinforcements (agro waste derivatives + synthetic ceramic materials) are usually superior to that of the single reinforced AMCs. The hybrid reinforcement with improved wear resistance usually exhibits more of abrasive wear mechanism than the adhesive wear mechanism due to low debris on the surface

of the composites. The adhesion of debris on the surface of the composites increased the coefficient of friction and the wear rate. The worn surfaces of hybrid Al-Mg-Si/BLA- $\text{Al}_2\text{O}_3$  is shown in Fig. 9. The hybrid composites containing 2 and 3 wt% BLA showed less debris attached to the surface as compared to hybrid composites containing 4% BLA indicating abrasive wear mechanism.

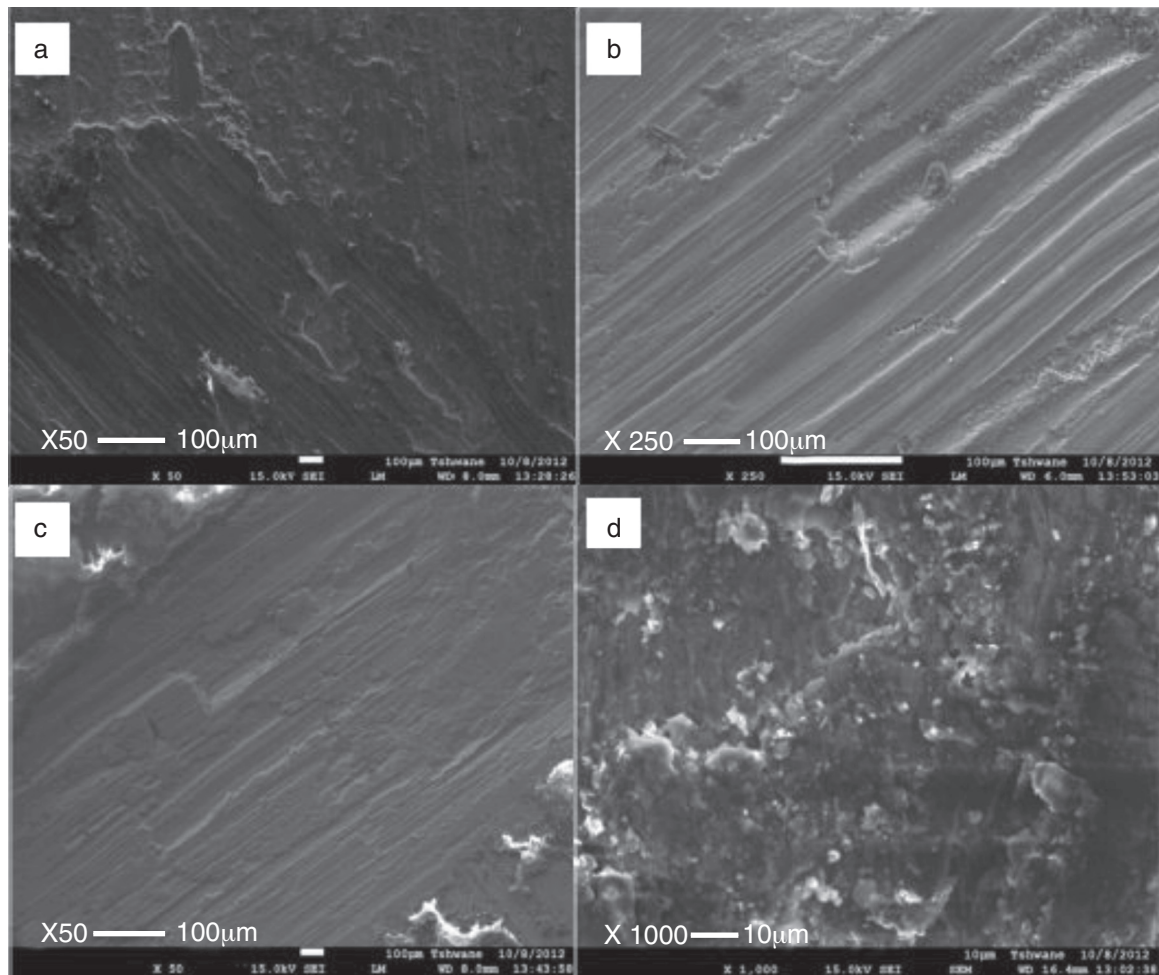
## 6. Production of aluminium matrix hybrid composites

Hybrid reinforced AMCs like the single reinforced AMCs are generally produced via two routes viz.: solid route and liquid route [55]. Solid route involves powder metallurgy techniques while liquid route, which entail compo-casting, squeeze casting and mostly stir casting techniques. Powder metallurgy techniques have become very important in the production of hybrid AMCs because composites having more volume fraction of the reinforcing particulates can be produced via this technique [56]. Also, hybrid reinforced AMCs reinforced with nano-sized particulates have been successfully fabricated using this technique [57]. Near-net shaped products that do not require post fabrication machining are easily produced using powder metallurgy. This technique is gaining lots of attention because particle clustering, wettability and formation of unwanted phases, which are some of the problems associated with liquid metallurgy route are easily avoided [58–62].

Stir casting technique has remained the most investigated technique for fabricating AMCs owing to its simplicity, flexibility and commercial viability [63,64]. Although concerns of homogenous distribution of reinforcing particles, porosity, wettability, particle clustering, segregation, interfacial reactions and formation of detrimental secondary phases have been widely reported; methods to contain these problems have been well reported [64,65]. Particle segregation and clustering can be avoided by optimizing mixing parameter such as stirring speed, rotation of stirrer, blade angle to stirrer axis [65] and also by adopting a two-step stir casting technique [66–68]. The wettability between the aluminium matrix and reinforcing materials has been improved by reinforcement coatings [69] and wetting agents such as  $\text{K}_2\text{TlF}_6$  [70], borax and magnesium [71]. Interfacial reaction and formation of secondary phases that are detrimental to the performance of the composites can be avoided by selecting reinforcing materials that do not undergo interfacial reaction such as alumina and boron carbide [72]. The application of hot isostatic pressing [73] or cold deformation [74] has been used to reduce the porosity in cast AMCs.

Mazaheri et al. [75] described friction stir processing as a novel technique for developing surface metal matrix composites (SMMCs). This has become necessary because metal matrix composites developed via stir casting and powder metallurgy are often reported to have increased strength and stiffness at the expense of ductility and toughness. Friction stir processing offers the opportunity of developing SMMCs with higher surface hardness [76,77] and improved creep resistance while maintaining the ductility and toughness of the metallic substrates [78]. The first result on SMMCs was published





**Fig. 9 – SEM images of worn surfaces of the (a) single reinforced Al-Mg-Si/10 wt%  $\text{Al}_2\text{O}_3$  composite (b) hybrid reinforced Al-Mg-Si/2 wt%/BLA-8 wt%  $\text{Al}_2\text{O}_3$  composite and (d) hybrid reinforced Al-Mg-Si/6 wt% BLA-6 wt%  $\text{Al}_2\text{O}_3$  composite reprinted from [54] with permission from ESG and the author.**

in 2003 by Mishra et al. [79]. This technique enhances the distribution of reinforcing particulates and reduces porosity in composites. It has been adopted as a post fabrication process to improve the properties of AMCs fabricated via powder metallurgy route [80]. Nano composites surfaces have also been developed on metallic substrates using FSP [81]. There have been successful attempt to develop bulk MMCs using FSP [82,83] but further research work should be done in this area in order to provide sufficient information for commercializing the process.

## 7. Summary and concluding remarks

This paper presents the different combination of reinforcements used in the synthesis of hybrid AMCs and how it influences its performance. The double synthetic ceramics reinforced hybrid AMCs despite showing good mechanical and tribological properties over the unreinforced alloys still need to be subjected to test under different corrosion media to ascertain its corrosion behaviour. Furthermore, comparison should be made between the hybrid composites with

the single reinforced grades in order to determine how much improvement is obtained when hybrid reinforcement is used. For the new generation of hybrid composites, which involve the use of agro and industrial waste derivatives, improved performance in comparison with the unreinforced alloy have been established. However, the degree of improvement of hybrid AMCs, which contains fly ash over the single reinforced AMC containing synthetic reinforcement still need to be studied. The hybrid AMCs reinforced with agro waste derivatives have shown that high performance levels can be maintained in AMCs at reduced production cost even at about 50% replacement of synthetic reinforcement with the agro waste. More agro waste should be investigated and further studies should be concentrated on how to optimize the production process to determine the optimum processing parameters. This will serve as a basis for producing hybrid MMCs on a commercial scale using agro and industrial waste. The most common technique used in the production of hybrid AMCs are stir casting and powder metallurgy which are utilized even at commercial scales. Finally, there is need for more research investigation to harness the benefits of the recently developed friction stir processed surface AMCs and bulk AMCs.

## Conflicts of interest

The authors declare no conflicts of interest.

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