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Journal of Materials Research and Technology
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Review Article

Characterization of hybrid aluminum matrix composites for advanced applications – A review



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ARTICLE INFO

Article history:

Received 2 December 2014

Accepted 5 May 2015

Available online 22 June 2015

Keywords:

Aluminum hybrid composites

Reinforcement

Mechanical behavior

Tensile strength

ABSTRACT

Hybrid aluminum matrix composites (HAMCs) are the second generation of composites that have potential to substitute single reinforced composites due to improved properties. This paper investigates the feasibility and viability of developing low cost-high performance hybrid composites for automotive and aerospace applications. Further, the fabrication characteristics and mechanical behavior of HAMCs fabricated by stir casting route have also been reviewed. The optical micrographs of the HAMCs indicate that the reinforcing particles are fairly distributed in the matrix alloy and the porosity levels have been found to be acceptable for the casted composites. The density, hardness, tensile behavior and fracture toughness of these composites have been found to be either comparable or superior to the ceramic reinforced composites. It has been observed from the literature that the direct strengthening of composites occurs due to the presence of hard ceramic phase, while the indirect strengthening arises from the thermal mismatch between the matrix alloy and reinforcing phase during solidification. Based on the database for material properties, the application area of HAMCs has been proposed in the present review. It has been concluded that the hybrid composites offer more flexibility and reliability in the design of possible components depending upon the reinforcement's combination and composition.

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<http://dx.doi.org/10.1016/j.jmrt.2015.05.004>

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1. Introduction

Metallic matrix composites (MMCs) reinforced with ceramic particles are very promising materials for structural applications due to excellent combination of properties. MMCs combine the properties of the metallic alloys (ductility and toughness) and the ceramic reinforcements (high strength and high modulus) leading to a superior profile of characteristics [1-2]. The aluminum matrix composites (AMCs) represent a class of MMCs possessing properties like low density, high stiffness and strength, superior wear resistance, controlled co-efficient of thermal expansion, higher fatigue resistance and better stability at elevated temperature. Due to this, these composites are used for the design of a wide range of components for advanced applications [3]. It has been found that the use of AMCs in engine applications can reduce the overall weight, fuel consumption and pollution in the automobiles and aircrafts [4,5]. AMCs reinforced with either silicon carbide (3.18 g/cm^3) or alumina (3.9 g/cm^3) particles are attractive materials for such applications [4-6]. These reinforcements are denser than those of aluminum alloys (2.7 g/cm^3) and increases the weight of the composites depending on the reinforcement's contents [7]. Moreover, the addition of ceramic particles to the Al-alloy increases the hardness of composite and makes machining of developed composite more difficult. Such problems can be solved by the use of multiple reinforcements in the aluminum alloy. The ceramic reinforcements possess superior strength than any other type of reinforcement and because of the fact, these are used as a primary

reinforcement for development of hybrid composites. However, the secondary reinforcements reduces the cost as these are readily available and weight as they have lower density of the hybrid composites [8,9]. The properties of the hybrid reinforcements (primary and secondary) can be combined to achieve optimization of material properties. Moreover, the use of stir casting technique for fabrication of AMCs reduces the cost the composites, as it is economical, simple to perform and highly productive method [3,10].

Nowadays, there is growing concern in the production of HAMCs with better physical and mechanical properties [11,12]. Recent research investigations have revealed that agro/industrial waste materials such as fly ash, graphite, rice husk ash, etc., can be successfully used as a complementary reinforcement in AMCs [13-17]. In addition to this, two ceramic phases can also be used for development of hybrid composites [9]. Further, the use of hybrid reinforcements improves the performance of the composites by introducing new features. First of all, these materials can reduce the cost of aluminum composites [13,14]. Secondly, the weight of the composites can be controlled due to lower density of these materials [15]. Thirdly, these composites can also offer comparable or even superior physical and mechanical properties [16,17].

The present study deals with the characterization of aluminum based hybrid composites developed by stir casting for advanced applications. The potential of a wide range of secondary reinforcements has been explored for the development of HAMCs and the application area of these composites has been proposed. The focus is on the optimization of parameters for various properties of composites. Further, the influence of reinforcement's type and contents on the material properties has also been reviewed and discussed.

2. Literature review

2.1. Microstructural features

The first task during fabrication of composites is to obtain the uniform distribution of reinforcing particles in the matrix alloy. Secondly, it is also essential to prevent segregation/agglomeration of particles during the progress of solidification. Chawla and Chawla [18] have proposed that morphology, type of reinforcements and distribution of reinforcing particles have significant contribution in the aggregate characteristics profile of the composites. According to Hanumanth and Irons [2], the variables that govern the distribution of particles are solidification rate and fluidity of the melt, type of reinforcements, the method of particle incorporation and wettability of particles in the melt. The addition of magnesium can be useful in improving the wettability between the reinforcing particles and the alloy melt. In addition, mechanical stirring in the semi-solid state can also be used to obtain the uniform distribution of reinforcing particles. The study of microstructure is quite useful in evaluating the distribution of reinforcing particles in the matrix alloy. The results of various studies regarding the microstructural features of HAMCs have been presented below.

Boopathi et al. [19] have studied the microstructures of aluminum alloy (Al 2024) reinforced with different compositions

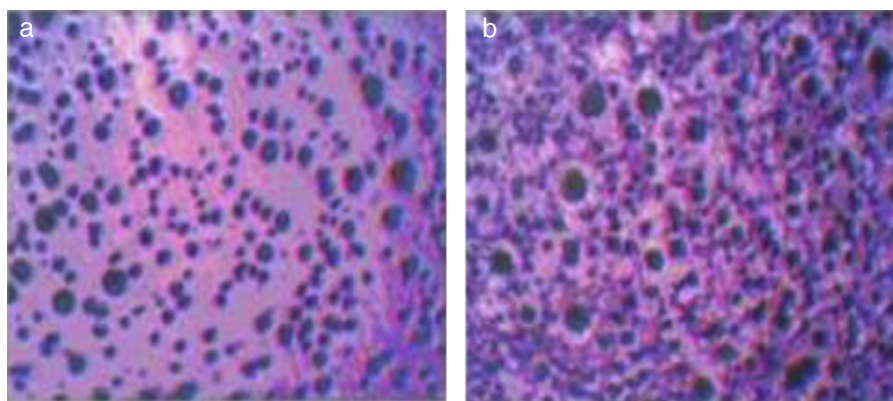


Fig. 1 – Optical micrograph of Al 2024/(10%SiC + 10% fly ash) (a) before etching and (b) after etching [19].

of fly ash, SiC and their mixtures. It has been observed that the particles were not uniformly distributed in single reinforced composites and segregation of particles was clearly visible. This was attributed to the gravity-regulated segregation of the particles in the melt. But, the micrographs of Al/SiC/fly ash hybrid composites indicate uniform distribution of particles at various concentrations (Fig. 1). The X-ray diffraction (XRD) analysis of the HAMCs confirms the presence of reacted SiC, fly ash, SiC–fly ash mixtures. The presence of aluminum and magnesium particles was also revealed during the microstructural investigations.

According to another investigation conducted by Rajmohan et al. [20], the hybrid reinforcements (SiC and mica particles) were uniformly distributed in Al356 alloy. The aluminum, carbon, silicon and oxygen particles were clearly visible in the energy dispersive X-ray spectroscopy (EDS) profile (Fig. 2). The scanning electron micrograph (SEM) images of composites are the evidence of successful incorporation of hybrid reinforcements in the Al-matrix. The clustering of SiC particles in matrix was attributed to their lower thermal conductivity and heat diffusivity than the alloy melt. The hotter SiC particles heats up the surrounding melt and delays the solidification process. Generally, the SiC particles are accumulated in the interdendritic regions and geometrical trapping by

dendrites is not observed in the micrographs. This suggests that SiC particles are always pushed by dendrite fronts during solidification process [21,22].

Prasad and Shobha [23] have observed the microstructural characteristics of hybrid composites reinforced by SiC and rice husk ash (RHA) particles. The uniform distribution of reinforcing particles was revealed during the examination. The presence of RHA and SiC particles was also confirmed in the micrographs of hybrid composites (Fig. 3). The results of above studies indicate that it is possible to obtain nearly uniform distribution of particles in the hybrid composites. But, various parameters need to be controlled and optimized during fabrication process. However, the successful incorporation of reinforcing particles shows that it is possible to obtain the hybrid composites with isotropic set of properties.

2.2. Physical properties

Generally, the ceramic reinforcements increase the density of the base alloy during fabrication of composites. However, the addition of lightweight reinforcements reduces the density of the hybrid composites [6,24–26]. Boopathi et al. [19] have evaluated the experimental values of density for the Al/SiC, Al/fly ash and Al/SiC/fly ash composites. The density of these

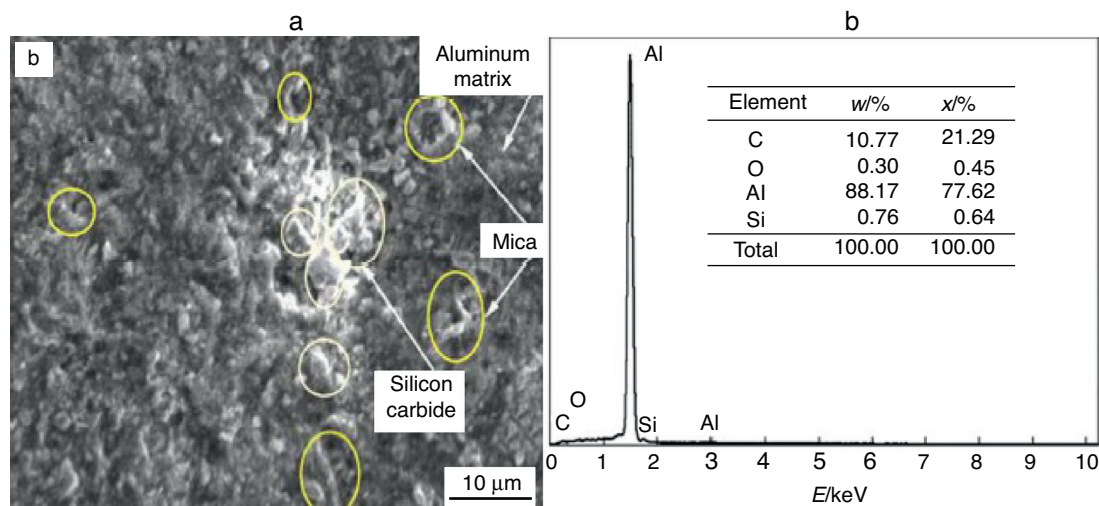


Fig. 2 – SEM images of (a) Al/10%SiC-3%mica composites (b) EDS spectrum of Al/10%SiC/3%mica [20].

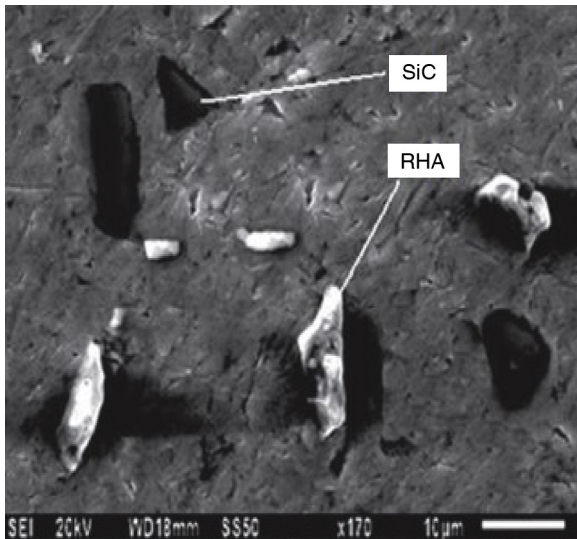


Fig. 3 – SEM image of hybrid composite [23].

composites decreased linearly due to lower density of SiC, fly ash and SiC-fly ash particles (Fig. 4). The study indicates that the interface between matrix and reinforcing particles is perfect. Similar results i.e. the density decreases with increase in fly ash contents have also been observed for fly ash reinforced composites in the studies conducted by Rao et al. [27] and Gnjadi et al. [28].

Rajmohan et al. [20] have reported that the density of mica reinforced hybrid composites was higher than the density of ceramic reinforced composites. The density of the hybrid composite increased with increase in mica contents. The results are in line with those presented by Sahin [29], who found that the density increased linearly with increase in the contents of reinforcing particles. The increase in the density indicates that particle breakage may not have any significant influence on the composites and the interfacial bonding between the particles and matrix is perfect. The presence of some porosity levels may be due to improper casting or pull out of particles during grinding and polishing. According to Alaneme et al. [24], there exists slight porosity in the hybrid composites and the use of BLA, SiC as multiple reinforcements does not increase the porosity level in the hybrid composites. The porosity levels in hybrid composites are much lower than the maximum acceptable value [30,31]. In another study

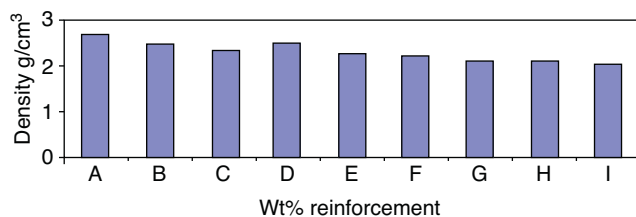


Fig. 4 – Graph showing variation in density with different composition (A = Al, B = Al + 5% SiC, C = Al + 10% SiC, D = Al + 5% fly ash, E = Al + 10% fly ash, F = Al + 5% SiC + 5% fly ash, G = Al + 5% SiC + 10% fly ash, H = Al + 10% SiC + 5% fly ash, I = Al + 10% SiC + 10% fly ash) of hybrid MMCs [19].

conducted by Alaneme et al. [26], a maximum of 6% reduction in density was observed for hybrid composites (with RHA and Al_2O_3) in comparison with the ceramic reinforced composite. As the reinforcement contents of RHA were increased, the density of composites decreased linearly. This may be due to presence of silica in RHA, relatively lighter material. The lower porosity level is a good indicator of the reliability of the fabrication process: stir casting for the hybrid composites [30,31]. Prasad et al. [32] have observed that the density of $\text{Al}/x\%\text{SiC}/x\%\text{RHA}$, where $x=0-8$ wt.%, the hybrid composite decreased with increase in the reinforcement contents. The decrease in density of the hybrid composites was due to the lower density of secondary reinforcement (RHA particles). It has been observed that porosity increased with the increase in the reinforcement contents. The increase in porosity level was attributed to gas entrapment during mixing, hydrogen evolution, shrinkage during solidification and presence of air bubbles in the liquid alloy. Although, some porosity levels are inevitable during fabrication of MMCs, but it should be kept to a minimum level. The authors has reported that the volume fraction and size of reinforcing particles play an important role in controlling the porosity level and physical properties of the composites.

2.3. Mechanical behavior

2.3.1. Hardness

The particulate reinforcements with low aspect ratio are of much significance as far as hardness of the composites is concerned. According to Hutching [33], the particulate reinforcements such as SiC, Al_2O_3 and aluminide improve the hardness of MMCs. Miyajima and Iwai [34] have reported that the MMCs dispersed with particulate reinforcements were harder than the whisker and fiber reinforced MMCs. The contributions of several researchers regarding the effect of particulate reinforcement on the hardness of the HAMCs have been summarized below.

Boopathi et al. [19] have reported an increasing trend in the hardness of composite with increase in weight fraction of reinforcements. They observed maximum hardness for $\text{Al}/10\text{ wt.}\%\text{SiC}/10\text{ wt.}\%\text{fly ash}$ hybrid composites. This shows that incorporation of fly ash particles significantly improves hardness of the Al-matrix. In another study, Rajmohan et al. [20] have evaluated the hardness of the hybrid composites reinforced with different mass fractions of mica particles (for fixed 10 wt.% SiC). The result shows that the hardness value of $\text{Al}/10\text{ wt.}\%\text{SiC}/6\text{ wt.}\%\text{mica}$ composite is less as compared to $\text{Al}/10\text{ wt.}\%\text{SiC}/3\text{ wt.}\%\text{mica}$ composite. Low values of hardness and strength are favorable for improving machinability of composites. Songmene and Balazinski [35] have reported that the energy requirement for machining of ductile material was comparatively less and it may be due to the lower forces required to shear the material during machining process. The results show that hardness of the HAMCs increased more or less linearly with the fraction of mica particles.

Prasad and Shoba [23] have observed that the hardness of the hybrid composites ($\text{A356.2}/x\%\text{RHA}/x\%\text{SiC}$) was higher than the pure A356.2 alloy. The hardness of the alloy increases with addition of hybrid reinforcements and the increase in hardness may be due to presence of relatively hard ceramic

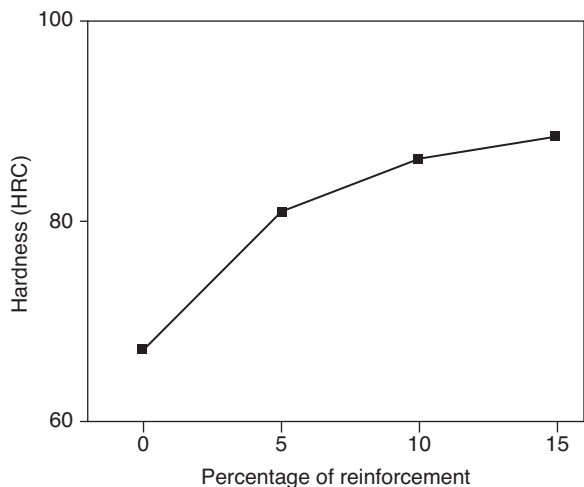


Fig. 5 – Hardness of unreinforced alloy and Al/0–15%SiC/3%B₄C hybrid composite at different volume fractions [36].

particles in the composite. It has also been reported that the addition of reinforcement (up to 8 wt.%) increases the hardness value by more than 50%.

Uvaraja and Natarajan [36] have investigated the influence of addition of SiC (0–15 wt.%) and B₄C (3 wt.%) particles on the hardness of Al-7075 alloy. Fig. 5 shows that the hybrid composites with higher hardness than unreinforced alloy could be achieved by reinforcing the Al-matrix with multiple reinforcements. This may be due to the fact that silicon carbide and boron carbide particles are harder than the alloy matrix and act as obstacles to the motion of dislocation. The Al/5 wt.%SiC/3 wt.%B₄C composite and the unreinforced alloy possessed similar hardness values. But, Al/15 wt.%SiC/3 wt.%B₄C composite possessed slightly higher hardness and low toughness as compared to the Al/10 wt.%SiC/3 wt.%B₄C composite. This may be due to the reason that higher percentage of particulate reinforcement is closely related to higher hardness and lower toughness. During the study, optimum weight percentage of the reinforcing particles was also evaluated to fabricate hybrid composites with superior hardness values. Alaneme et al. [24] have investigated the hardness of HAMCs reinforced with ceramics particles and agro waste ashes (RHA) and observed decrease in hardness value with increase in RHA contents. The four types of composites were developed: AI, AII, AIII, and AIV having weight ratio of RHA and alumina as 0:10, 2:8, 3:7 and 6:4 respectively to evaluate variation of hardness with RHA contents. The results show that the hardness of AII, AIII, AIV hybrid composite decreased by a fraction of 4.58%, 8.14% and 10.94%, respectively, in comparison with the single reinforced composite (AI). This trend was attributed to the presence of silica (SiO₂) in RHA. The silica has lower hardness level as compared to ceramics reinforcements [26,37]. Therefore, RHA contents have significant influence on the hardness of the composite.

Prasad et al. [32] have measured the BHN of Al/x%SiC/x%RHA, where x=0–8 wt.%, hybrid composites to characterize the age hardening behavior at a temperature of 155 °C. The composites were also subjected to aging at a

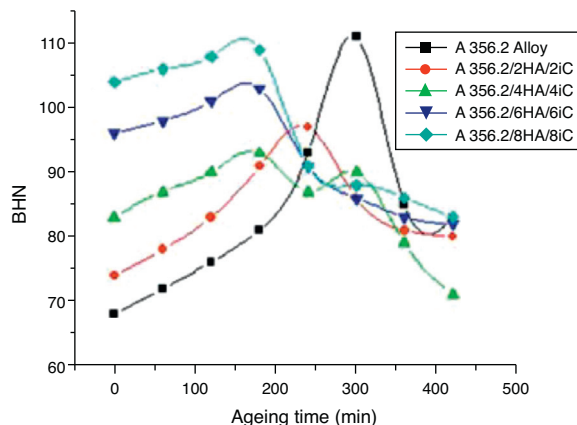


Fig. 6 – Brinell hardness versus the aging time for the alloy and hybrid composites [32].

load of 500 N. A steel ball indenter with diameter of 30 mm was used for a time period of 30 s. It was observed that the hardness of composites increased after age treatment (Fig. 6). The peak hardness was reported at lower aging time for the hybrid composites as compared to the Al-alloy (240 min for the A356.2/2%RHA/2%SiC hybrid composite, 180 min for A356.2/4%RHA/4%SiC, A356.2/6%RHA/6%SiC, and A356.2/8%RHA/8%SiC hybrid composites and 300 min for the Al alloy). The results presented by authors indicate that the addition of reinforcement to the aluminum matrix accelerates the aging kinetics due to the high dislocation density.

Suresha and Sridhara [38] have reported that the hardness of hybrid composites reinforced with SiC and Graphite particles increased up to reinforcement contents of 2.5 wt.% (equal for both reinforcements) and then decreased (Fig. 7). The increase was due to the addition of SiC particulates and the decrease was attributed to the overriding effect of soft graphite particles. The addition of graphite particles reduces the hardness value due to the increase in porosity levels. These results suggest that the presence of ceramics particles is beneficial for improving the resistance of the composites to indentation

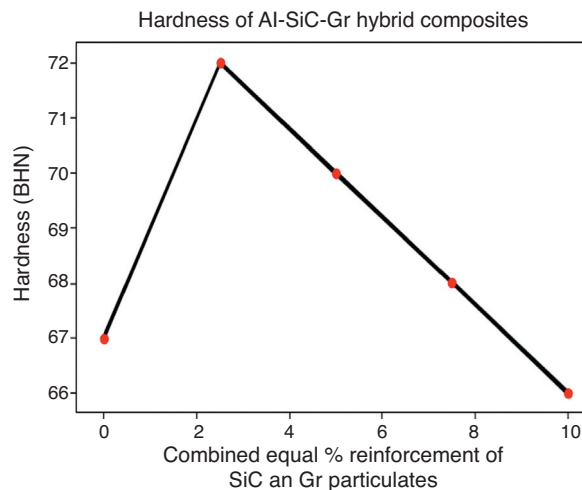


Fig. 7 – Hardness vs. reinforcement contents of Al/SiC/Gr hybrid composites [38].

and the presence of soft particulates such as graphite, RHA, BLA, etc. reduces the hardness value of composites.

2.3.2. Tensile behavior

Chen et al. [39] have reported that the elastic modulus and strength of the composites increased with addition of reinforcements. This was attributed to the strong interface between the reinforcement and the matrix alloy. Further, Thakur and Dhindaw [40] have observed that the improvement in interfacial strength and better dispersion of the reinforcing particles could be achieved by preheating the reinforcing particles during fabrication of composites. Generally, two types of the strengthening mechanisms have been reported in the AMCs i.e. direct and indirect strengthening [41]. According to Chawla and Shen [42], the direct strengthening arises as a result of the addition of harder and stiffer reinforcements in the soft matrix. Due to presence of hard phase in the composites, the applied load is transferred from the matrix to the reinforcement through the interface. This increases the resistance of composites to plastic deformation during application of external load [43]. The indirect strengthening occurs due to high thermal mismatch between the metallic matrix (having higher coefficient of thermal expansion) and the embedded particulates (with lower coefficient of thermal expansion) during cooling and solidification [44]. Therefore, a change in temperature will generate thermal stresses in the composites resulting in the formation of dislocations at the reinforcement/matrix interface. The increase in dislocation density contributes to the improvement in strength level of the composite [43]. The increase in reinforcement fraction or decrease in particle size increases the amount of indirect strengthening due to increase in dislocation density. This may be attributed to the availability of a larger interfacial area for dislocation punching to take place. Various observations regarding the strength of HAMCs are discussed below.

Boopathi et al. [19] have evaluated the strength of the HAMCs reinforced with SiC, fly ash and their mixtures. The results show that the tensile strength of composites is higher than the unreinforced Al-alloy. Tensile strength of unreinforced Al-alloy is 236 N/mm² and this value increases to 263 N/mm² for Al/10%fly ash composite, 265 N/mm² for Al/10%SiC composite and 293 N/mm² for Al/10%SiC/10%fly ash hybrid composite. This represents a significant improvement in the strength of hybrid composite as compared to the Al-matrix. The yield strength of the hybrid composites also increases with increasing contents of SiC and fly ash reinforcements [42]. This may be attributed to the increasing number of stress concentration points at the poles of the reinforcing particles. This leads to decrease in micro-yielding stress with increase in reinforcement's contents. The elongation of composites decreases due to presence of brittle particles. Elongation of unreinforced alloy is 19.4% and this value decreases to 11.9% for Al/10%SiC/10%fly ash hybrid composite. This represents 75% reduction of elongation for hybrid composite as compared to the unreinforced Al-matrix. Rajmohan et al. [20] have evaluated that the tensile strength of HAMCs reinforced with mica (0, 3, and 6 wt.%) and SiC (10 wt.% fixed). It has been reported that the tensile strength of the composites increased with increase in mass fraction of mica (up to certain value) and then it reduced. Fig. 8 shows that hybrid composite

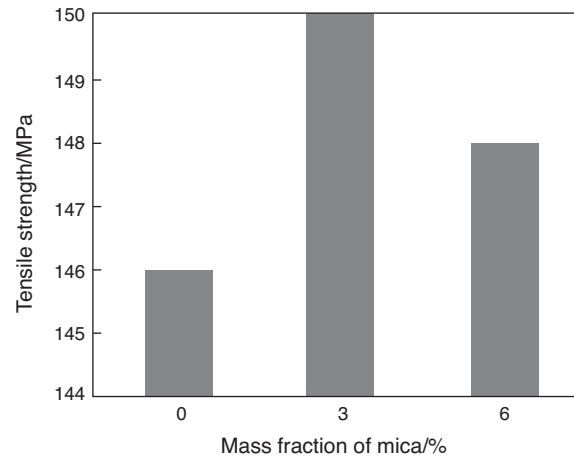


Fig. 8 – Tensile strength of composites with different content of mica [20].

reinforced with 3 wt.% of mica particles exhibits higher strength (150 MPa) than the strength of 6 wt.% mica reinforced composite (148 MPa).

Further, Alaneme et al. [24] have reported that the tensile strength and yield strength of the composites decreased with increase in BLA contents. The specific strength and percentage elongation of the hybrid composites also decreased with increase in BLA contents. The specific strength of the Al/2 wt.%BLA/8 wt.%SiC hybrid composite was comparable to the Al/10 wt.%SiC composite. But, the Al/3 wt.%BLA/7 wt.%SiC and Al/4 wt.%BLA/6 wt.%SiC hybrid composites possessed lower specific strength than the ceramic reinforced composite. Similar results were also observed in another study conducted by Alanama et al. [26]. It has been reported by the authors that the strength of hybrid composites containing alumina and RHA decreases with an increase in RHA percentage. The slight decrease in strength of composites was attributed to the reduction in the contribution of direct strengthening [41]. This may be due to the fact that elastic modulus of silica (a major constituent element of RHA) is of the order of 60–70 GPa (similar to pure aluminum). But, the elastic modulus of ceramics particulates (SiC or Al₂O₃) is of much higher value (the order of 300–450 GPa) [45,46]. Thus, the load carrying capacity of the hybrid composites will be dependent on the amount of ceramics particulates rather than RHA contents. However, the specific strength of Al/2 wt.%RHA/8 wt.%Al₂O₃ (45.5 MPa/g/cm³) hybrid composite was found to be higher than the ceramic reinforced composite (~2% higher). But, the Al/3 wt.%RHA/7 wt.%Al₂O₃ and Al/4 wt.%RHA/6 wt.%Al₂O₃ possessed lower specific strength (3.56% and 7.7% respectively) as compared to the ceramic reinforced composite. However, this also represents a modest improvement in the strength of these hybrid composites as compared to ceramic reinforced composite. The specific strength and percent elongation of the hybrid composites decreased with increase in contents of agro waste ashes with a few exceptions. Prasad et al. [32] have reported that the ultimate tensile strength (UTS) and yield strength (YS) of Al/x%SiC/x%RHA (x = 0–8 wt.%) hybrid composite increased with increase in the weight fraction of reinforcements, while the elongation decreased (Fig. 9).

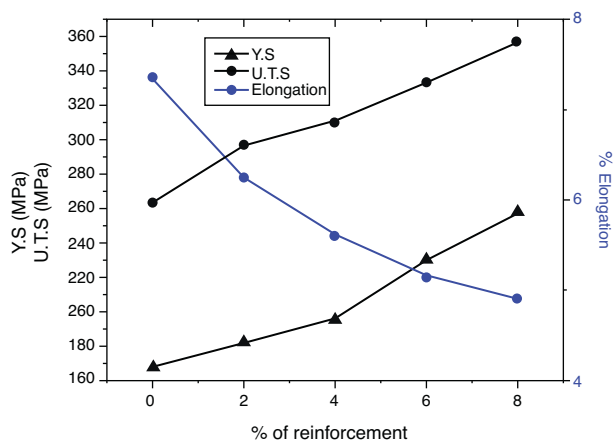


Fig. 9 – Variation in UTS, YS and elongation of hybrid composites with percentage reinforcement [32].

Here, SiC and RHA were used as hybrid reinforcements in equal proportions (0, 2, 4, and 6 wt.%) to characterize the composites. The authors also observed that the elongation decreased due to increase in UTS and YS of the composite. This may be due to presence of hard ceramic phase in the composites, which increases the brittleness in the composites developed by the authors.

It has also been reported in earlier studies that the strengthening of hybrid composites was due to increase in dislocation density with an increase in reinforcement percentage [23,32]. The SiC and RHA (in equal proportions) were used as the hybrid reinforcements in these studies. These composites are characterized by a large difference in the thermal expansion coefficient (CTE) of the matrix and the reinforcements (CTE of A356.2 is $21.4 \times 10^{-6}/^{\circ}\text{C}$, the CTE of RHA is $10.1 \times 10^{-6}/^{\circ}\text{C}$ and the CTE of SiC is $4.3 \times 10^{-6}/^{\circ}\text{C}$). The temperature stresses produced are partially released by generation of dislocation at the interface. The strengthening due to the difference in CTE can be measured in the form of yield strength contribution for geometrical necessary dislocations [47]. The dislocation density increases with an increase in reinforcement contents in the composite and the results are supported by the SEM images. Fig. 10 shows an increase in the

dislocations with percentage of reinforcement. Due to thermal mismatch between the matrix and reinforcements, the dislocations come into existence for fulfilling geometrical conditions. The dislocation density follows an increasing trend with increase in reinforcement contents leading to strengthening of hybrid composites.

2.3.3. Fracture toughness

The fracture toughness of the hybrid composites reinforced with SiC and BLA increased with increase in BLA contents [24]. Generally, the metallic composites reinforced with conventional ceramic particulates have poor fracture toughness values. The improvement in fracture toughness with increase in BLA content may be attributed to the presence of silica, which is a softer ceramic in comparison with SiC. The results obtained are validated by the fact that the fracture toughness of most of the engineering materials varies inversely with the yield strength [48,49]. The results are in line with those obtained by Alaneme et al. [26], who determined the fracture toughness values of hybrid composites by circumferential notched tensile (CNT) specimens. In this study, load–extension plots were used to evaluate the fracture toughness of the composites [50,51]. The hybrid composites containing 2 wt.% and 3 wt.% RHA contents possessed higher fracture toughness values as compared to the ceramics reinforced composite [26]. The primary mechanisms of fracture have been attributed to particle cracking, interfacial cracking or particle debonding [48]. Ceramic particulates are generally hard and brittle. Therefore, ceramics have poor tendency to resist rapid crack propagation [52]. Further, the micro-mechanism responsible for improvement in fracture toughness of hybrid composites (containing 2 wt.% and 3 wt.% RHA) needs to be investigated. However, it is clear that the addition of 2–3 wt.% RHA did not deteriorate the fracture toughness of the Al_2O_3 reinforced aluminum composites. In another study, Ravesh and Garg [53] have reported that the toughness of Al/SiC/fly ash hybrid composites increased with increase in weight fraction of reinforcement. This may be due to proper dispersion of reinforcing particles in the matrix or strong interfacial bonding between the matrix and reinforcement. In the study presented by authors, maximum value of toughness was obtained for the hybrid composite containing 10 wt.%SiC and 5 wt.%fly ash contents.

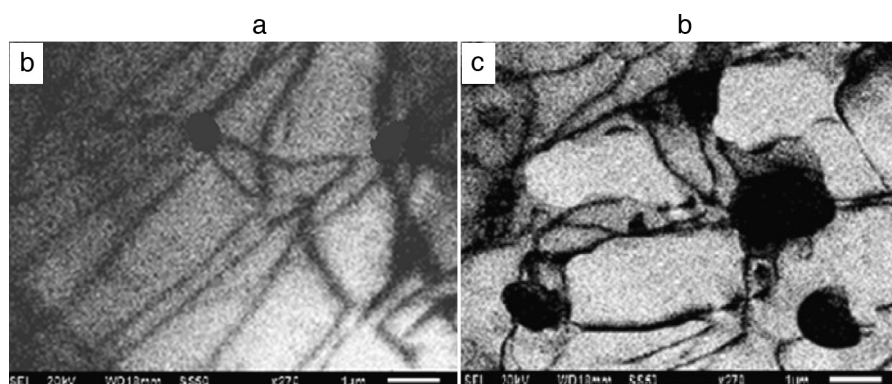


Fig. 10 – SEM images showing dislocation arrangement in (a) 6% hybrid composite (b) 8% hybrid composite [23].

Table 1 – Properties of Al based alloys with and without the reinforcements in weight fractions.

Composition	Density/porosity (g/cm ³)	Tensile/yield (N/mm ²)	Elong. (%age)	Hardness (BHN)	Fracture toughness (MPa m ^{1/2})	Ref.
Al 2024	2.6	236/220	19.4	80	–	[19]
Al 2024 + 5%SiC	2.4	248/236	19.0	85	–	
Al 2024 + 10%SiC	2.3	265/257	18.2	87	–	
Al 2024 + 5%FA	2.4	245/233	16.3	80	–	
Al 2024 + 10%FA	2.2	263/252	15.8	83	–	
Al 2024 + 5%SiC + 5%FA	2.2	276/262	14.4	88	–	
Al 2024 + 5%SiC + 10%FA	2.1	278/269	13.8	90	–	
Al 2024 + 10%SiC + 5%FA	2.1	285/275	12.8	93	–	
Al 2024 + 10%SiC + 10%FA	2.0	293/287	11.9	95	–	
Al 356	2.6	234/165	3.5	70	–	[20]
Al 356 + 10%SiC	3.0	146	–	100	–	
Al 356 + 10%SiC + 3%Mica	3.1	150	–	115	–	
Al 356 + 10%SiC + 6%Mica 3.16	148	–	–	110	–	
Al–Mg–Si	2.81	–	–	67	–	
Al–Mg–Si + 10%SiC	2.74/1.14	155/118	23	77	7	[24]
Al–Mg–Si + 2%BLA + 8%SiC	2.69/0.9	146/110	16	74	9	
Al–Mg–Si + 3%BLA + 7%SiC	2.66/1.24	138/98	14	72	10	
Al–Mg–Si + 4%BLA + 6%SiC	2.64/1.06	125/90	12	67	12	
Al–Mg–Si	2.81	–	–	67	–	
Al–Mg–Si + 10% Al ₂ O ₃	2.79/1.02	120/92	12	75	11	[26]
Al–Mg–Si+2%RHA + 8%Al ₂ O ₃	2.68/2.3	110/82	12	69	12	
Al–Mg–Si + 3%RHA + 7% Al ₂ O ₃	2.66/1.9	106/78	10	66	11	
Al–Mg–Si + 4%RHA + 6% Al ₂ O ₃	2.62/1.9	102/70	08	64	10	
A356	2.73/3.7	263/168	7.35	68	–	[32]
A356/2%SiC/2%RHA	2.70/2.1	296/182	6.25	74	–	
A356/4%SiC/4%RHA	2.69/1.5	310/196	5.6	83	–	
A356/6%SiC/6%RHA	2.69/1.3	333/120	5.15	96	–	
A356/8%SiC/8%RHA	2.66/0.3	356/258	4.9	104	–	
Al 7075	–	–	–	67	–	
Al 7075 + 3%B ₄ C	–	–	–	77	–	[36]
Al 7075 + 3%B ₄ C + 5%SiC	–	–	–	82	–	
Al 7075 + 3%B ₄ C + 10%SiC	–	–	–	85	–	
Al 7075 + 3%B ₄ C + 15%SiC	–	–	–	88	–	

3. Discussion

3.1. Database for properties of HAMCs

In this section, properties of hybrid composites are presented to identify the materials with adequate performance for various advanced applications. The data regarding the properties of hybrid composites reinforced with different compositions and combinations of reinforcements is presented in Table 1. The results clearly indicate that the agro/industrial waste materials are becoming attractive choice to researchers, engineers and scientists as an alternative reinforcement for aluminum based composites [19,23,24,26,32]. These materials cannot be considered as a single reinforcement in the Al-alloy due to presence of greater contents of silica (with lower elastic modulus). But, due to their low cost, fairly good mechanical properties, high specific strength, non-abrasive nature, eco-friendliness and bio-degradability characteristics, these could be explored as a complementary reinforcements for development of hybrid composites.

In addition to this, some other particulates such as mica, B₄C have also shown significant potential as a secondary

reinforcement for development of hybrid composites. It has also been observed that the physical and mechanical behavior of produced composites is influenced by composition and type of the reinforcement (hard or soft). Results show that several modifications can be employed to enhance the properties of these composites (by reinforcing Al-matrix with suitable combination of reinforcements). Generally, the properties like density, tensile strength, hardness, fracture toughness, etc. can be optimized for design of various automotive and aerospace components by selecting appropriate reinforcements. Based on this data, the application area of these hybrid composites has been proposed in next section.

3.2. Characterization and applications

3.2.1. Al/SiC/FA hybrid composites

The hybrid composites reinforced with SiC and fly ash (FA) possess superior mechanical and physical properties as compared to the single reinforced composite (Al/SiC or Al/FA) or unreinforced alloy (Al2024). The properties of the composites presented in Table 1 indicate that the density and the percent elongation of the Al/10 wt.%SiC/10 wt.%fly ash hybrid

composite reduces by 54% and 75% respectively in comparison with the pure alloy. However, the hardness, tensile strength and yield strength of the hybrid composite increases by 17%, 57% and 67% respectively. The fracture toughness of the HAMCs increases with increase in reinforcement contents. Thus, it can be concluded that the mechanical properties of the hybrid composites are improved with an increase in reinforcement's contents. Contradictory, the density and elongation of the hybrid composite is decreased as compared to the unreinforced aluminum. In overall, the strength to weight ratio of the HAMCs is improved as compared to unreinforced alloy. Hence, these composites offer good potential to be used in automotive components. The fly ash is considered as a waste material without any gainful applications. Therefore, it can be readily used for development of composites. From the results, it can be concluded that instead of Al/SiC or Al/fly ash composites, the Al/SiC/fly ash hybrid composite could be considered as an exceptional material for design of various components in automotive sector. The essential requirements for the applications of this composite are lightweight, low cost and enhanced mechanical properties.

3.2.2. Al/ceramics/BLA hybrid composites

Table 1 also shows the variations in the properties of the hybrid composites developed by reinforcing SiC and agro waste (bamboo leaf ash) in the Al–Mg–Si alloy. The hardness, ultimate tensile strength and yield strength of the composites decreases with increase in BLA content. The hardness of hybrid composites with 2 wt.%, 3 wt.% and 4 wt.%BLA contents reduced by 4.58%, 8.14%, and 10.94%, while the tensile strength of these composites decreases by 7.97%, 15.6%, and 23.29%, respectively, in comparison with the ceramic reinforced composite (Al–Mg–Si/10 wt.%SiC). The specific strength and percent elongation of the hybrid composite decreases with an increase in BLA contents, and the fracture toughness of hybrid composite is improved. It may also be noted that the difference between the specific strength of the single and hybrid reinforced composite is less than 2%. The decrease in the density of the hybrid composite with increase in BLA contents indicates that there is adequate potential for the development of low weight-high performance hybrid composites for various automotive components.

3.2.3. Al/ceramics particulates/RHA hybrid composites

The alumina particles and rice husk ash (RHA) can offer another combination as hybrid reinforcements for aluminum matrix. Table 1 shows that the hardness of hybrid composite with 2 wt.%, 3 wt.% and 4 wt.% RHA contents reduces by 4.58%, 8.14% and 10.94% respectively, while the tensile strength is reduced by 3.7%, 8% and 13%, respectively, in comparison to the ceramic reinforced composite (Al–Mg–Si matrix/10 wt.%Al₂O₃). The specific strength, percentage elongation and fracture toughness of the hybrid composites reinforced with 2 wt.% RHA is higher than the Al₂O₃ reinforced composite and other hybrid composites. Table 1 also indicates that if the SiC and RHA are added in equal percentage (up to 8 wt.%), all the mechanical properties of the composite are improved while density is reduced.

The RHA has lower density (0.3–1.6 g/cm³) and large availability in most part of the world. It is also a cheap material

and requires simple processing. The above observation shows that depending on the weight percentage of RHA in the hybrid reinforcement, lighter and cheap HAMCs can be produced. The comparable or even superior mechanical properties of the hybrid composites confirms that RHA has great promise to serve as a complementary reinforcement for the development of high performance components.

3.2.4. Al/SiC/mica hybrid composites

Table 1 shows that mica and SiC can be successfully used as hybrid reinforcements in Al356 alloy. The mechanical behavior of the hybrid composites varies with the reinforcement contents of mica. The tensile strength of hybrid composites is less as compared to the unreinforced composite. The density and hardness of the hybrid composites are higher as compared to the unreinforced composite. The increasing trend in hardness can improve the indentation characteristics and therefore the hardness of the components. Therefore, SiC and mica reinforced composites can be used for developing automotive components, where hardness and strength are the primary requirements.

3.2.5. Al/SiC/B₄C hybrid composites

Table 1 indicates that the hardness of the composites increases linearly with increasing contents of hard ceramic reinforcements. A maximum of 33% improvement in the indentation characteristics of the composites can be obtained by reinforcing Al-matrix by 18% of hard reinforcement phase. Although, the hard ceramics may increase the weight of the hybrid composites, but the results indicate an improvement in indentation characteristics of the composites. As these composites exhibits better hardness and toughness as compared to single ceramic reinforced composites, therefore they are preferred for heavy-duty vehicles and high wear resistance applications.

4. Future scope

Currently, the design of high performance-low cost components is receiving much attention from material researchers. The same can be attained by the consideration of industrial and agro-waste materials as green reinforcements in aluminum matrix composites. The disposal of these materials faces environment related problems. Therefore, recycling of these waste materials by converting it into green material is a focus of the current research. Due to environment friendliness, energy efficiency and cost-effectiveness, these materials exhibit good market potential as a reinforcement material for composites. Fly ash, red mud, palm oil fuel ash (POFA), palm oil clinker (POC), rice husks, coconut husk and sugarcane bagasse are some of the waste materials that have potential to be utilized in construction and automotive industries. Vast researches have been conducted and developments are still advancing for successful utilization of waste materials as partial reinforcement in composites. The present study shows that the HAMCs offer unique combination of mechanical and physical properties, which are scarcely attainable with the use of ceramic reinforced composites. The HAMCs could be applied in the design of components for automobiles, aircrafts,

marine structures and facilities, defence assemblies, sports and recreation among many others. The notable advantages of HAMCs are the relatively low cost, lightweight and higher strength to weight ratio in comparison ceramic reinforced composites. However, the investigations regarding wear properties of these composites needs to be carried out under different parametric conditions since very limited literature corresponding to wear of such composites is available. Finally, it can be said that there is an immense potential, scope and opportunities for the researchers in the field of prediction and improvement of characteristics of the HAMCs.

5. Conclusions

The present discussion confirms that the application of HAMCs in various automotive components seems to be feasible. The review of investigations on the various aspects of HAMCs provides several conclusions regarding the influence of various parameters on the performance of the composites. Firstly, the microstructures of the HAMCs fabricated by stir casting route have been found to be stable with uniformed distribution of reinforcing particles. Consequently, the HAMCs can be fabricated with different combinations of reinforcements to achieve desirable mechanical properties not available in ceramic reinforced composites. The density of HAMCs increases with increasing contents of ceramic reinforcements, while incorporation of partial reinforcements like fly ash, rice husk ash, mica, etc. reduces the density of composites. However, the porosity levels obtained in these composites are within acceptable limits. The mechanical properties of HAMCs are reviewed with respect to strength and it is evident that the composition and type of the reinforcements control the mechanical properties of the composites. It has also been observed from the literature that the synthetic reinforcements like SiC or alumina can be combined with complementary reinforcements to obtain desirable properties for the composite. The study also reveals that the HAMCs can be considered as a replacement for conventional materials in various advanced applications.

Conflicts of interest

The authors declare no conflicts of interest.

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