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Mechanical behaviour of stir cast aluminum matrix composites reinforced with silicon carbide and palm kernel shell ash

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Abstract. Microstructural analysis and mechanical behaviour of aluminum matrix composites (AMCs) reinforced with palm kernel shell ash (PKSA) and silicon carbide (SiC) were studied. The AMCs containing 6, 8, 10 and 12 wt.% reinforcements, with weight ratios of 0:1, 1:3, 1:1, 3:1 and 1:0 (PKSA: SiC) were produced using stir casting method. % Porosity, hardness, tensile strength (UTS), ductility and fracture toughness were determined following standard procedures, while Scanning electron microscopy (SEM-EDS) was used for structural characterization. The results show that the composites produced have improved hardness. The UTS improved with increase in PKSA attaining maximum value at reinforcement weight ratio 1:1 and then decreases, the 6 wt.% reinforcement being the only exception. The ductility of the composites was lower than the unreinforced aluminum alloy with the SiC single-reinforced having the lowest. Also Fracture toughness was observed to be less than the unreinforced aluminum alloy with the SiC single reinforced having the lowest value. The PSKA:SiC weight ratio 1:1 gave the best property combination with optimum properties in terms of UTS (175.48MPa), ductility (8.61) and fracture toughness [6.5MPa(m)$^{1/2}$].

Keywords: Aluminium matrix composites / hybrid reinforcement / palm kernel shell ash / silicon carbide / mechanical properties / microstructure

1 Introduction

The development of sustainable materials to meet functional, cost and environmental concerns has continued to attract interest from materials scientists, policy makers and end users. Within the context of composites materials, the use of recycled materials, renewable materials, or waste products as constituents in the composite design is considered as meeting the requirement for sustainable materials. For such composite systems to be deemed acceptable, they must fulfill the primary materials selection functions. In the case of aluminum matrix composites, an excellent combination of high specific strength and stiffness, low thermal coefficient of expansion, good corrosion and wear properties cannot be traded off. This quest for economical and energy-efficient materials, with better physical, mechanical, thermal and tribological properties, in the automobile, aerospace and other applications is tailoring research in the direction of consideration of agro-waste derivatives as reinforcement substitute for the development of hybrid reinforced aluminum matrix composites (HAMCs) [1,2]. Hybrid aluminum matrix composites present new generation of aluminum matrix composites (AMCs) that have the potential to substitute single reinforced composites due to improved properties [3–5]. Recent researches have shown that agro/industrial wastes are effective as contemporary reinforcements in HAMCs [2,6]. Research into these industrial and agro waste materials, also regarded as sustainable materials has identified constituents including SiO_2, Al_2O_3, Fe_2O_3, $CaCO_3$ which are excellent candidates for reinforcement particulates [7]. Other advantages of these agro-waste products include ready availability at little or no cost, conservation and protection of the environment, and often lower densities in comparison with most technical ceramics such as silicon carbide, boron carbide, and alumina [1,7]. Furthermore, they are reported to offer the possibility of producing low cost-light weight composites without compromising their mechanical and tribological properties [1]. Substantial work has been done and promising results reported on the use of agro-wastes as

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Table 1. Chemical composition of aluminum ingot used.

Al	Si	Fe	Cu	Mn	Mg	Cr	Ni
98.69	0.4461	0.2178	0.0028	0.0181	0.4717	0.003	0.0056
Zn	Ti	Be	Ca	Pb	V	Zr	Sn
0.0085	0.0093	0.0001	0.0005	0.0063	0.0085	0.0017	0.007

Table 2. Chemical Composition of PKSA after conditioning.

CaO	MgO	K_2O	Na_2O	MnO	ZnO	Al_2O_3	SiO_2	SiO_3	Fe_2O_3
0.0163	0.7932	1.6827	1.2794	0.5166	0.9288	5.5342	35.0847	42.1017	12.0624

hybrid reinforcement in aluminum matrix composites production as can be verified by Alaneme et al. [8], Alaneme and Adewale [9], Fatile et al. [10], Alaneme and Sanusi [11], Alaneme et al. [12], and Muni et al. [13]. Concerning the use Palm Kernel Shell Ash (PKSA) as reinforcement in producing aluminum matrix composites, the following works have been published: Oladele and Moses [14] studied The Effect of Palm Kernel Shell ash on the Mechanical properties of As-cast Aluminium Alloy Matrix Composites. Recycled aluminium alloy from cylinder of an automotive engine block were used as matrix. Oyedeji et al. [15] worked on "Characterization of Al-Mg-Si Alloy Reinforced with Optimum Palm Kernel Shell Ash (PKSA) Particle and its Consequence on the Dynamic Properties for Aerospace Application". Oyedeji et al. [16] investigated "The Effect of Palm Kernel Shell Ash Reinforcement on Microstructure and Mechanical Properties of Al-Mg-Si Metal-Matrix Composites". This study reported the microstructure and mechanical properties of Al-Mg-Si matrix reinforced with varying weight percentages (0, 4, 6 and 8 wt.%) of palm kernel ash (PKSA). Thorough appraisal of these literatures shows that PKSA has only been studied as single reinforcement constituent in AMCs. The design of AMCs with the use of PKSA as part of hybrid reinforcement system to the best of our knowledge, has not received much attention in literature. Reports from hybrid reinforcement systems where agro-waste ashes are used as complementary reinforcement to conventional reinforcement such as SiC or Al_2O_3, show that due to factors such as peculiarities in terms of density, wettability, volume fraction, composition, and mechanical characteristics, the behaviour of these hybrid reinforcements cannot be extrapolated from what is known from existing systems. Hence, the need for an exclusive study on the mechanical behaviour of AMCs reinforced with PKSA and SiC is undertaken. The focus of this paper is to report on the mechanical properties: Tensile strength, Hardness, Ductility and Fracture toughness of Aluminum Matrix Composites produced using PKSA as a complementing (Hybrid) reinforcement for silicon carbide (conventional reinforcement), in the development of high performance low-cost AMCs, due to the high cost and limited availability of the synthetic or conventional reinforcements [7,17].

Nigeria is a country endowed with abundant agricultural resources, one of which is the "Tropical Palm Tree (Elais Guinensis)" from which palm kernel shell is derived as an agro-waste. The integration of PKSA as a reinforcement in composites systems will assist in alleviating the disposal challenges associated with Palm Kernel Shells.

2 Experimental

2.1 Materials used

Aluminium (6063) alloy sourced from Nigerian Aluminium Extrusion Company (NIGALEX), Oshodi in Lagos State, Nigeria was selected as metal matrix for the composite production. Spark spectrometric analysis was used to determine the chemical composition of the aluminum alloy and the result is presented in Table 1. Silicon Carbide particulates were sourced from a local vendor of chemical and industrial materials, while Palm kernel shell was sourced from Ohaji/Egbema Local Government Area of Imo state, Nigeria.

2.2 Method

2.2.1 Processing of palm kernel shell ash

Palm kernel shells were obtained washed and sun dried for a period of four days. After drying, they were burnt in a local pit kiln using a perforated steel container (grate) until it was totally charred. After burning, they were ground to fine particles using a laboratory size ball mill and then sieved using 250 mesh sieves. The filtrates were further heat-treated by exposing them to a temperature of about 560 °C in a Muffle furnace for a period of six hours to enable thorough formation of the ash and discharge of any organic constituents. The ash was allowed to cool in the furnace after which representative samples were taken for chemical analysis which was performed at Soil Science Laboratory, National Root Crops Research Institute, Umudike, Abia State. The result of the Chemical analysis is shown in Table 2.

2.2.2 Composite production

In this research, the aluminum hybrid reinforced composites were produced by "double–step stir casting process" in accordance with Alaneme and Aluko [18] and Singh et al. [19]. The aluminum was melted in a gas-fired crucible furnace at 700 ± 20 °C, while the various mixture ratios of

Table 3. Summary of sample designation.

% Reinforcement	Sample	Reinforcement composition	Reinforcement composition ratio	Description of sample
		% PSKA: % SiC	PSKA : SiC	
0%	A (control)	0:0	0:0	Alloy (unreinforced)
	B1	0:100	0:1	SIC only
	B2	25:75	1:3	Hybrid Composite
6%	B3	50:50	1:1	Hybrid Composite
	B4	75:25	3:1	Hybrid Composite
	B5	100:0	1:0	PKSA only
	C1	0:100	0:1	SIC only
	C2	25:75	1:3	Hybrid Composite
8%	C3	50:50	1:1	Hybrid Composite
	C4	75:25	3:1	Hybrid Composite
	C5	100:0	1:0	PKSA only
	D1	0:100	0:1	SIC only
	D2	25:75	1:3	Hybrid Composite
10%	D3	50:50	1:1	Hybrid Composite
	D4	75:25	3:1	Hybrid Composite
	D5	100:0	1:0	PKSA only
	E1	0:100	0:1	SIC only
	E2	25:75	1:3	Hybrid Composite
12%	E3	50:50	1:1	Hybrid Composite
	E4	75:25	3:1	Hybrid Composite
	E5	100:0	1:0	PKSA only

PKSA:SiC (0:1, 1:3, 1:1, 3:1, and 1:0) of silicon carbide and palm kernel shell ash was preheated to about 300°C in a separate crucible. The preheated mixture of the reinforcement (SiC and PKSA) was carefully poured into the molten aluminum and then manually stirred until it became pasty at 600 ± 10 °C. The pasty mixture (composite) was reintroduced into the furnace and heated to molten state again at 740 ± 25 °C, and then stirred using a mechanical stirrer for about three minutes (to ensure uniform dispersion in the molten aluminum) after which it was poured into an already prepared sand mould. This process was carried out for all the compositions of the composite. After fettling, the samples were machined into various standard specimens for tensile, hardness, and fracture toughness tests according to standard specifications.

2.2.3 Sample designation

The composites produced were grouped based on the varying proportions of the reinforcements. The various reinforcement compositions that were studied are 6, 8, 10 and 12 wt.%; and for each of the group, varying ratios of mixture of the reinforcements PKSA:SiC (0:1, 1:3, 1:1, 3:1, and 1:0); were chosen in order to study the effect of the PKSA reinforcement compared with the standard reinforcement SiC_p; and also the effect of combination of PKSA and SiC_p reinforcements on the properties of the composites. Table 3 summarizes the various sample designations and the corresponding composite compositions.

2.2.4 Density and percent porosity measurement

Experimental density measurements were done using Archimedes principle while theoretical densities were determined using the rule of mixtures according to equation (1). The values of the experimental densities obtained were used to evaluate the amount of porosity in the composites produced in accordance with Ikubanni et al. [20] and Kumar et al. [21]. The percentage porosity (% Porosity) for each sample produced was calculated using equation (2).

$$\rho_c = \left(\rho_{al} \times M_{f_{Al}}\right) + \left(\rho_{SiC} \times M_{f_{SiC}}\right) + \left(\rho_{PKSA} \times M_{f_{PKSA}}\right) \tag{1}$$

where $^{2}_{c}$ is density of composite, $M_{f_{Al}}$ is density of composite, $M_{f_{Al}}$ is mass fraction of aluminum, ρ_{SiC} is density of Silicon carbide, $M_{f_{SiC}}$ is mass fraction of Silicon carbide, ρ_{PKSA} is density of Palm Kernal Shell ash, and M_{fPKSA} is mass fraction of palm kernel shell ash.

$$\%\,\text{Porosity} = \frac{\text{Theoritical density} - \text{Experimental density}}{\text{Theoriticaldensity}} \times 100. \tag{2}$$

2.2.5 Microstructural examination

Representative samples of the as-cast composites were polished and etched using Kellerâ s reagent, after which they were examined using the Carl Zeiss Smart Evo 10 Scanning Electron Microscope having accessories for EDS analysis.

2.2.6 Mechanical testing of composites

Vickers hardness tests were carried out on the composites produced in accordance with ASTM E92-17 [22] standard. The test was conducted at room temperature and was carried out at several locations on the sample surface to avoid the possible effect of the indenter resting on the hard reinforcement particle. The statistical average of the readings was reported as the hardness value of the composites.

Tensile tests were carried out using Universal testing machine at nominal strain rate of 10^{-4}/s (quasi-static strain rate) until fracture. The machining and testing procedures were in accordance with ASTM E8M-15a [23] standard. Repeat tests were carried out to ascertain consistency in the results obtained.

The fracture toughness K_{1c} of the composites was determined using the circumferential notch test (CNT) approach in accordance with Alaneme et al. [24]. The as-cast samples were machined as follows: gauge length of 30 mm, diameter (D) of 6 mm, circumferential notch diameter (d) of 4 mm and notch angle of 60°. K_{1c} values were calculated using equation (3). SEM-fractographs of representative samples were also obtained to determine the fracture mode for the AMCs.

$$K_{1c} = \frac{P_f}{D^{3/2}\left[1.72\left(\frac{D}{d}\right) - 1.27\right]} \tag{3}$$

where K_{1C} id fracture toughness, P_f is load at fracture, D is diameter, and d is circumferential Notch diameter.

3 Results and discussion

3.1 Microstructure examination

Representative SEM micrographs of samples comprising of Samples **A** (Control, 0 wt.% reinforcement), **B3** (6 wt.% reinforcement with 1:1 ratio), **C3** (8 wt.% reinforcement with 1:1 ratio), **D3** (10 wt.% reinforcement with 1:1 ratio), and **E3** (12 wt.% reinforcement with 1:1 ratio), are presented in Figures 1a-1 e). From observation, uniform distribution of the reinforcements was reasonably achieved. In Figures 2a and 2b, the various peaks (Al, Fe, Si, Mg, Na) observed in the EDS profiles suggest the presence of SiC and PKSA in the AMCs produced.

3.2 Composite density and percent porosity

The results obtained for the composite density and percent porosity measurement are shown in Table 4. It can be observed that the experimental densities are lower than the theoretical densities. For 6 wt.% composites, the theoretical densities reduced with the addition of varying ratios of the reinforcements starting from 0:1 through to 1:0 (PKSA:SiC) ratios. The single reinforced composite (sample B1) with SiC only, was found to have highest density, higher than the unreinforced Al (6063) alloy. This is due to the higher density of SiC (3.21 g/cm^3) compared to that of Al alloy (2.7 g/cm^3). The other single reinforced composite with only PKSA (sample B5) had the lowest densities due to the very low density of PKSA (0.93 g/cm^3). The same trend of behaviour was observed for the other classes of the composites (8 wt.%, 10 wt.% and 12 wt.%), which is an indication that the introduction of varying percentages of the PKSA reinforcement into the composites effectively reduced the theoretical densities of the composites produced. The observed variation between the theoretical density and the experimental density is an indication of the existence of porosity in the composites produced. However porosities less than 4% are considered permissive in the cast metal matrix composites, that is, it doesnâ t compromise the material properties [25].

3.3 Mechanical properties of composites

3.3.1 Hardness

The hardness values of the composites produced are presented in Figure 3. For 6 wt.% class of reinforcement, it can be observed that the hardness of the composites increased by approximately 19% from 51.1HV for the unreinforced matrix to 60.8 HV for the single reinforced composite containing 100% SiC but decreased as PKSA is added until the point of total replacement of SiC with PKSA in sample containing 1:0 ratio of reinforcement (56.4 HV). The hardness values of the composites produced were also observed to increase with increase in wt.%. of reinforcement. The percentage increase in hardness for each of the reinforced composite produced with respect to the unreinforced (A) is summarized in Table 5. From the table, the single reinforced composites containing 100% SiC are observed to have the highest values of hardness in each of the classes. As the quantity of SiC decreases and PKSA increases, hardness decreases. This behaviour of the Hardness can be explained by the fact that SiC, possesses higher hardness than SiO_2 and SiO_3 which are the principal constituent in PKSA [5,26]. This increase observed between the unreinforced alloy and the SiC single reinforced composite can be attributed to the introduction of the hard SiC particulates, while the progressive decrease in hardness that follow can be due to gradual substitution of the SiC particles with the relatively softer PKSA particles. Generally, it is expected that the hardness of the single and hybrid reinforced composites are higher than that of the unreinforced Al(6063) matrix due to the presence of the ceramic reinforcements which improved the hardness of the composites [27].

3.3.2 Ultimate tensile strength

The ultimate tensile test results obtained for the various composites produced are presented in Figure 4. For the class of 6 wt.% reinforcement, it was observed that the UTS value for the single reinforced composite with reinforcement ratio of 0:1, when compared to the unreinforced alloy, reduced by approximately 15% from

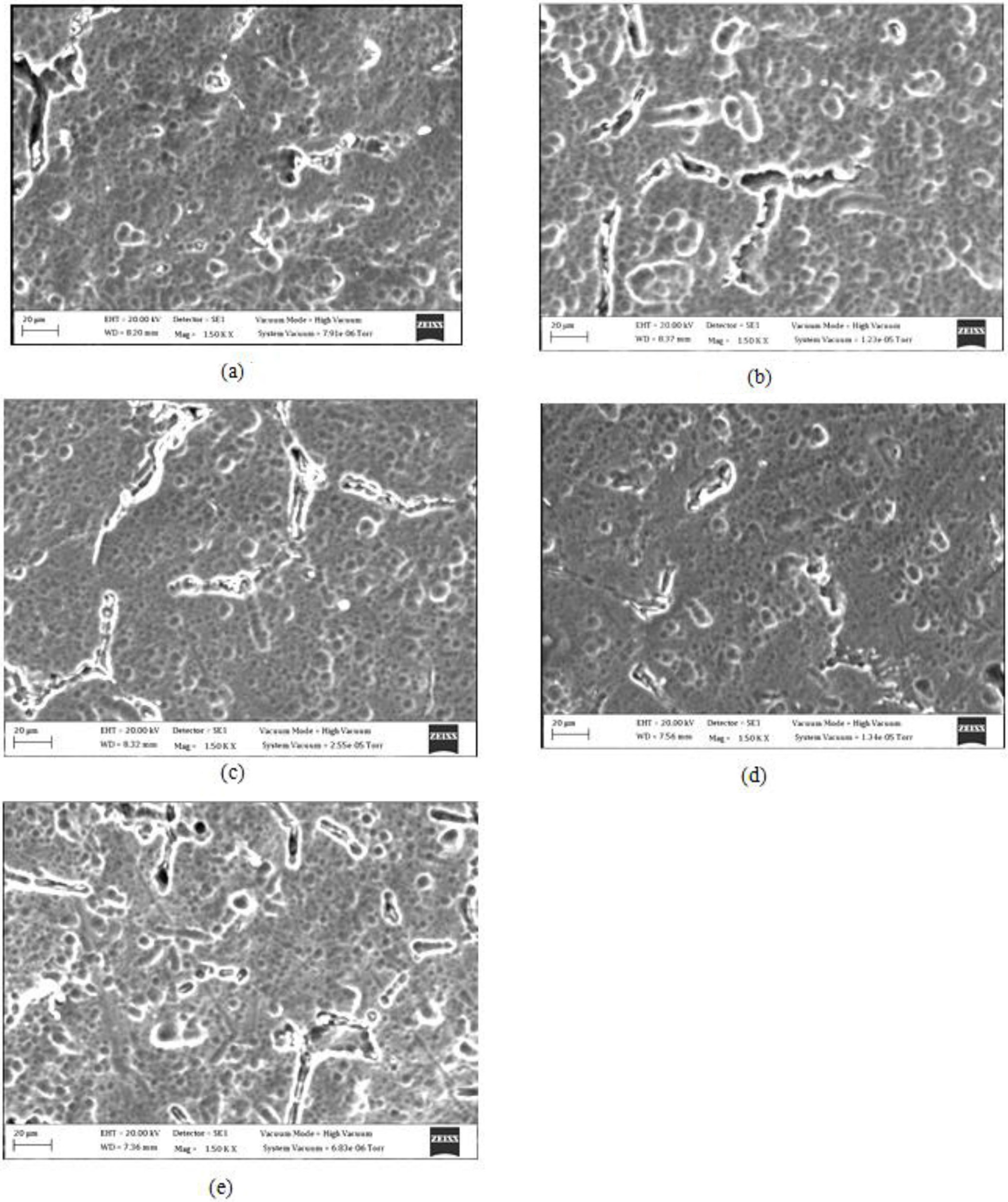
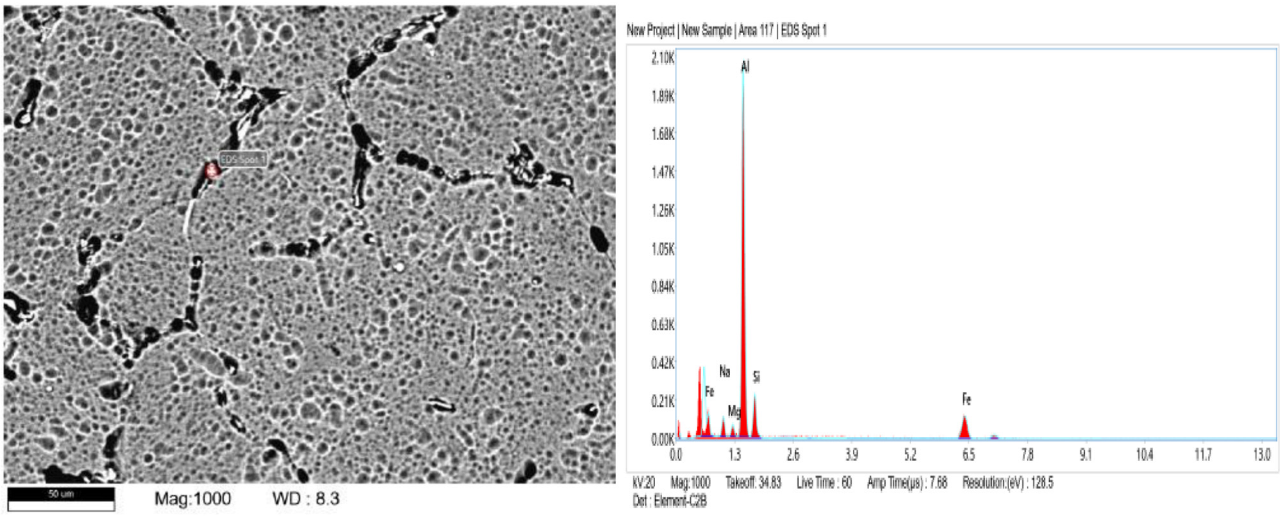
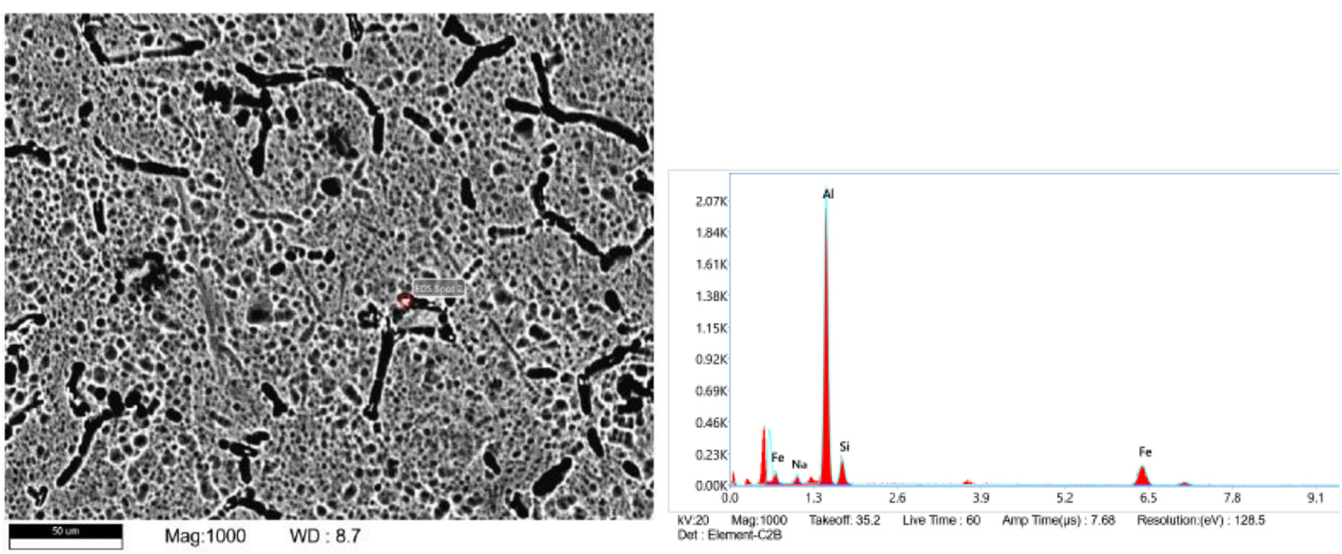


Fig. 1. SEM micrograph of representative samples of the composites: (a) Control; (b) B3; (c) C3; (d) D3; (e) E3.



(a)



(b)

Fig. 2. (a) Sample C3 (8 wt.% reinforcement with 1:1 ratio), (b) sample E3 (12 wt.% reinforcement with 1:1 ratio.

112 MPa to 95.63 MPa. But as the amount of PKSA in the composite increased, the UTS value increased progressively up to the highest UTS value of 129.75 MPa (15.84%) for the composite containing 1:1 reinforcement ratio, after which it decreased progressively to UTS value of 111.03 MPa (0.87%) for the composite with 1:0 reinforcement ratio. The same trend, but with higher values of UTS, was observed for composites with 8 wt.% and 10 wt.% of reinforcement, except for 12 wt.% reinforcement, which had a slight variation with the highest UTS value being attained by the composite with 3:1 reinforcement ratio. Table 6 shows the percentage decrease or increase observed in the strength with reference to the unreinforced alloy A.

Generally, it can be stated that the UTS of the reinforced composites with 8 wt.%, 10 wt.% and 12 wt.% were significantly enhanced with the highest UTS value of 175.48 MPa (56.68%) for the 8 wt.% composite with 1:1 reinforcement ratio. Furthermore, it was observed that the Hybrid composites had better UTS values than the single reinforced composites. This can be attributed to the synergic effect of particle strengthening and dispersion strengthening mechanisms with the trend such that SiC particles being relatively harder than PKSA particles, the samples with higher proportion of SiC undergo more of particle strengthening. As the proportion of PKSA increases, dispersion strengthening gradually dominates, attaining an optimal effect at reinforcement ratio 1:1. Secondly, thermal mismatch between the high expansion metallic matrix and the low expansion ceramic reinforcements, effective transfer of stress from matrix to the reinforcements and interactions between the dislocations and particulates (strain hardening effect), and grain

Table 4. Values of experimental, theoretical densities & % porosity.

% Reinforcement	Sample Designation	Reinforcement Mix	Experimental Density	Theoretical Density	% Porosity
		PSKA:SiC	(g/cm^3)	(g/cm^3)	
0% Control	A	0:0	2.664	2.7	1.33
	B1	0:1	2.665	2.731	2.42
	B2	1:3	2.671	2.696	0.93
6%	B3	1:1	2.649	2.663	0.53
	B4	3:1	2.59	2.629	1.48
	B5	1:0	2.568	2.596	1.08
	C1	0:1	2.722	2.741	0.69
	C2	1:3	2.658	2.696	1.41
8%	C3	1:1	2.622	2.65	1.06
	C4	3:1	2.586	2.606	0.77
	C5	1:0	2.526	2.561	1.37
	D1	0:1	2.734	2.751	0.62
	D2	1:3	2.685	2.695	0.37
10%	D3	1:1	2.586	2.639	2
	D4	3:1	2.56	2.582	0.85
	D5	1:0	2.498	2.526	1.11
	E1	0:1	2.68	2.761	2.93
	E2	1:3	2.641	2.694	1.97
12%	E3	1:1	2.563	2.627	2.44
	E4	3:1	2.49	2.558	2.66
	E5	1:0	2.445	2.491	1.85

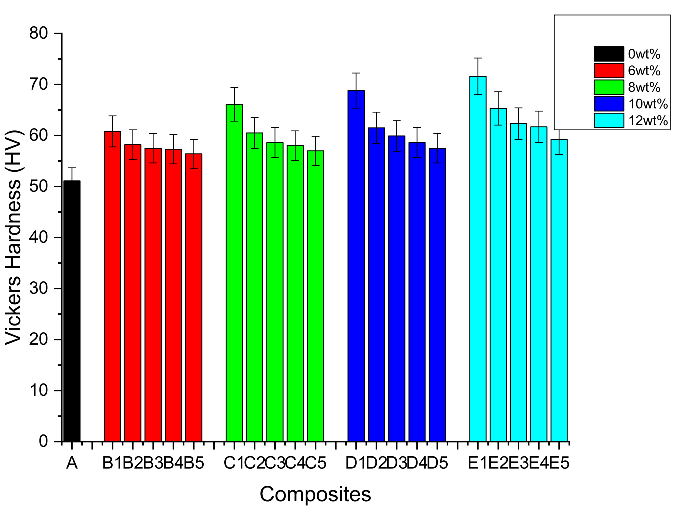


Fig. 3. Variation of vickers hardness for composites produced.

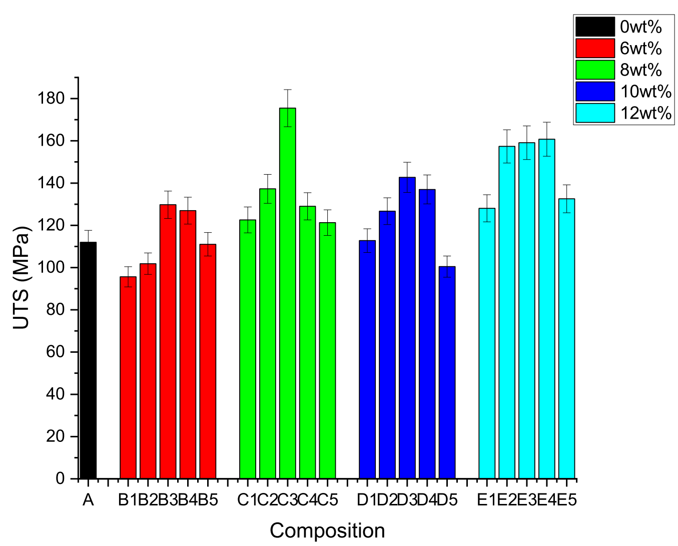


Fig. 4. Variation of ultimate tensile stress (UTS) for composites produced.

refinement of the matrix (Hall-Petch effect) can all be good reasons for the strengthening of the composites produced [2,3,7,28–30].

3.3.3 Percent elongation (ductility)

The results of the % Elongation, which is a measure of ductility of the composites, are represented in Figure 5. For the 6 wt.% reinforced AMCs, the ductility decreased by 44.54% from 9.61 for the unreinforced to 5.33 for the single reinforced containing 100% SiC reinforcement. With the gradual replacement of SiC reinforcement with PKSA, the ductility improved by 10.41%, attaining a value of 8.61 for the composite containing 1:1 ratio of reinforcement after which it decreased by 34.62%, to ductility value of 6.28 for the composite containing 1:0 ratio of reinforcement (only PKSA). The ductility of the single AMCs

Table 5. Percentage increase in hardness (HV).

Sample	Hardness (HV)	% Increase in HV
A (Control)	51.1	
B1	60.8	19
B2	58.2	14
B3	57.5	13
B4	57.3	12
B5	56.4	10
C1	66.1	29
C2	60.5	18
C3	58.6	15
C4	58	14
C5	57	12
D1	68.8	35
D2	61.5	20
D3	59.9	17
D4	58.6	15
D5	57.5	13
E1	71.6	40
E2	65.3	28
E3	62.3	22
E4	61.7	21
E5	59.2	16

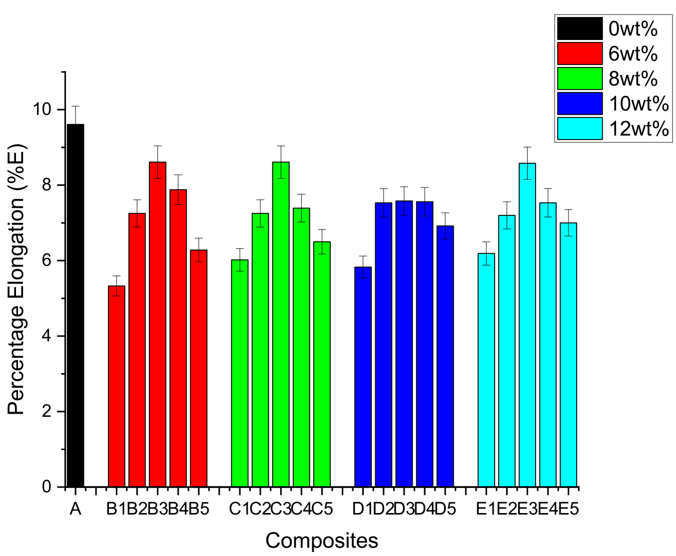


Fig. 5. Variation of % elongation of composites produced.

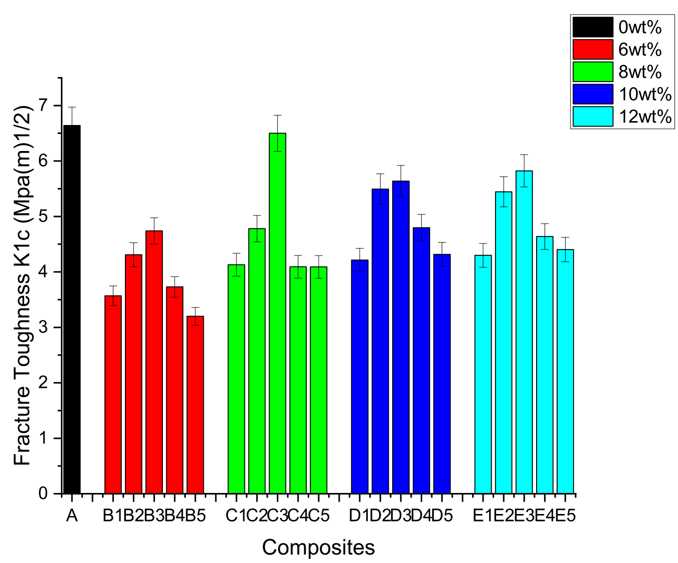


Fig. 6. Variation of fracture toughness K_{1c} for composites produced.

with ratio 1:0, containing only PKSA, was observed to be higher than that of the other single reinforced composite with 0:1 ratio, containing only SiC_p. The enhancement in percentage elongation observed in the hybrid reinforced composites could be as a result of increase in the weight percent of the PKSA which is a relatively softer ceramic compared to SiC [5].

Generally, the ductility of the unreinforced Al(6063) matrix was found to be higher than the ductility of the composites produced. This reduction in the ductility between the unreinforced aluminum alloy and the composites produced can be explained with the knowledge that the incorporation of these hard and brittle ceramic

Table 6. Percentage decrease/increase observed in the strength with reference to the unreinforced alloy (A).

Sample	UTS value	% Increase (+) or % Decrease (−)
A (Control)	112	
B1	95.63	–14.60
B2	101.85	–9.10
B3	129.75	+15.84
B4	126.95	+13.34
B5	111.03	–0.87
C1	122.54	+8.93
C2	137.27	+22.56
C3	175.48	+56.68
C4	129.00	+15.18
C5	121.29	+8.29
D1	112.76	+0.68
D2	126.69	+13.11
D3	142.71	+27.42
D4	136.99	+22.31
D5	100.46	–10.30
E1	128.07	+14.35
E2	157.38	+40.52
E3	159.08	+42.04
E4	160.77	+43.54
E5	132.56	+18.36

particles will increase the brittleness and the hardness of the composites, thereby reducing ductility and increasing hardness [5,7,21].

3.3.4 Fracture toughness

The fracture toughness values of the composites produced are presented in Figure 6. The results are taken to be reliable because the nominal plane strain conditions were met for the specimen configuration used for the CNT testing. It is observed that the fracture toughness of the Single reinforced composite with 100% SiC reinforcement dropped from K_{1c} value of 6.64 MPa(m)$^{1/2}$ for the unreinforced Al(6063) matrix to 3.57 MPa(m)$^{1/2}$ representing approximately 46%. With the introduction of PKSA reinforcement, the fracture toughness increased by 20.73%, from 3.57 MPa(m)$^{1/2}$ to 4.31 MPa(m)$^{1/2}$ for composite with 1:3 ratio of reinforcement and then increased further by 10%, to 4.74 MPa(m)$^{1/2}$ for composite with 1:1 ratio of reinforcement after which it decreased by 21.31%, to 3.73 MPa(m)$^{1/2}$ for composite with 3:1 reinforcement ratio and decreased further by 14.21%, to 3.20 MPa(m)$^{1/2}$ for the composite with 1:0 ratio of reinforcement containing 100% PKSA. The other classes of composites (8 wt.%, 10 wt.% and 12 wt.%), showed the same trend of behaviour and the composite with 1:1 reinforcement ratio in 8 wt.% class, has the highest value of 6.50 MPa(m)$^{1/2}$ among the single and hybrid reinforced composites. Generally, it observed that the fracture toughness of the composites produced are lower than that of the unreinforced Al(6063). The decrease in the fracture toughness from that of the unreinforced Al(6063) matrix is as a result of the introduction of ceramic SiC and silica particulates into the Al(6063) matrix, that are hard, rigid and brittle and will be more susceptible to rapid crack propagation and constitute an effective barrier to flow when subjected to strain under an applied load. The enhancement in fracture toughness observed in the hybrid reinforced composites as a result of increase in the weight percent of the PKSA up to composites with 1:1 ratio of reinforcement can be due to the presence of silica from PKSA, which is a relatively softer ceramic compared to SiC [5]. The decrease that follows for higher weight ratios of PKSA could be as a result of increased volume percent of PKSA which likely may lead to clustering of particles [31]. Representative Fractographs were obtained for some selected samples and are presented in Figure 7. It can be seen that the granular structures, indicative of a dominantly brittle fracture failure were conspicuous in the representative composite compositions examined, which is consistent with the low fracture toughness values observed in the AMCs.

3.4 Property comparison

Table 7 compares some mechanical properties of aluminum matrix hybrid composites involving agro-waste reinforcements (at varying wt.% reinforcements as well as varying wt.% ratios) in other works already available in literature with the present work. This highlights the various works done and the mechanical properties evaluated. From Table 7, it can be observed that the various values obtained

Table 7. Mechanical properties comparison.

Article	Reinforcement used	Wt.% Reinforcement		Wt.% Ratio	Mechanical Properties Evaluated.	
			Hardness	UTS (MPa)	% Elongation	Fracture toughness [MPa(m)$^{1/2}$]
Alaneme et al. (2013)a	Bamboo leaf Ash and Silicon carbide	10 wt.% 2:8	76.33 HVN	150	18	7.6
Alaneme et al. (2013)b	Rice Husk Ash and Silicon Carbide	10 wt.% 25:75	–	158.4	17	8
Fatile et al. (2014)	Corn Corb Ash and Silicon Carbide	10 wt.% 1:9	91 HVN	182	24	10
Alaneme et al. (2016)	Groundnut Shell Ash and Silicon Carbide	10 wt.% 25:75	63 HRV	149	13	8
Muni et al. (2019)	Rice Husk Ash, Copper and Magnesium	10 wt.% 6:3:1	54.1 HRB	95.2	7.75	
		12 wt.% 8:3:1	57 HRB	97.1	6.37	
Oyedeji et al. (2021)	Palm Kernel Shell Ash (Single Reinforcement)	6 wt.% –	91 HRB	–	–	–
		8 wt.% –	88 HRB	–	–	–
		6 wt.% 50:50	57.5 HVN	129.75	8.61	4.74
Present study	Palm Kernel Shell Ash and Silicon Carbide	8 wt.% 50:50	58.6 HVN	175.48	8.61	6.5
		10 wt.% 50:50	59.9 HVN	142.71	7.58	5.64
		12 wt.% 50:50	62.3 HVN	159.08	8.58	5.82

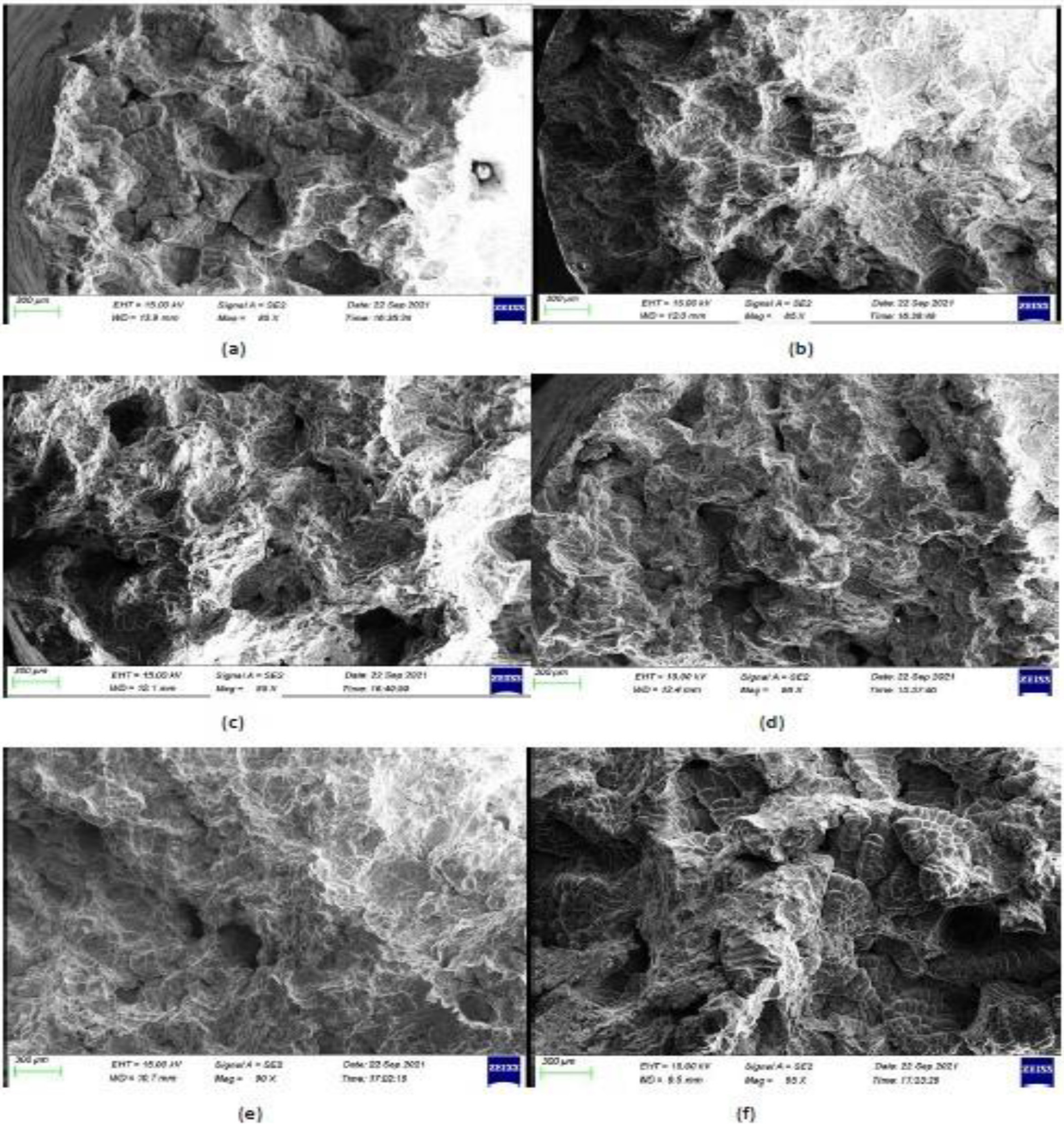


Fig. 7. SEM fractographs of some samples (a) Samples **A** (Control, 0 wt.% reinforcement), (b) **B3** (6 wt.% reinforcement with 1:1 ratio), (c) **C3** (8 wt.% reinforcement with 1:1 ratio), (d) **D3** (10 wt.% reinforcement with 1:1 ratio), and (e) **E3** (12 wt.% reinforcement with 1:1 ratio), (f) **E5** (12 wt.% reinforcement, 1:0 ratio).

to a great extent agree with that in other existing works (considering 10 wt.% reinforcement which is applicable to most available works).

4 Conclusion

The mechanical behaviour of single and hybrid PKSA and SiC reinforced composites was studied. From the results obtained the following conclusions were made:

- The composites produced have improved hardness with 100% SiC reinforced in each class having the highest hardness which decreased as the PKSA gradually replaces the SiC having the highest hardness % increment of 40% in sample E1 (0:1) of 12 wt.%.
- The tensile strength (UTS) improved from 0:1 as the PKSA gradually replaces the SiC attaining a maximum at 1:1 and then decreases until 1:0, except for a variation in 6wt.%. Optimum UTS of 175.48 MPa was observed in 8 wt.% reinforcement with ratio 1:1.
- Ductility of the composites produced was lower than the unreinforced (9.61). The SiC single reinforced has the lowest value which increases as the PKSA gradually replaces SiC, attaining optimum value at 1:1 ratio in all classes of reinforcement.
- Fracture toughness was observed to be less than the unreinforced with the SiC single reinforced (0:1) having the lowest value which gradually increases as the PKSA replaces the SiC attaining an optimum value at sample 1:1 and then decreases down to sample 1:0.
- 8 wt.% reinforcement with ratio 1:1 was found to have optimum properties in terms of UTS (175.48MPa), Ductility (8.61) and Fracture toughness [6.5 MPa$(m)^{1/2}$].
- The locally sourced and cheaply processed, stir cast PKSA hybrid reinforced AMCs have mechanical properties comparable to that of established agro-waste based hybrid reinforced AMCs.

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