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Scientific paper
ISSN 0351-9465, E-ISSN 2466-2585
https://doi.org/10.5937/zasmat2204386O

Zastita Materijala 63 (4)
386 - 394 (2022)

Improving the mechanical and wear behaviours of reinforced aluminium alloy with animal waste particulates ash

ABSTRACT

The research work investigated the mechanical and wear behaviours of aluminium alloys reinforced with cow horn ash (CHA) which is cost-effective and environmentally-friendly materials at different weight percentages (0 wt. % to 15 wt. %) at 3 wt. % interval. The cow horn ash was characterized by X-ray fluorescence (XRF). The matrix and the composites morphology were studied using a scanning electron microscope (SEM) for the distribution of cow horn ash particles within the matrix. The wear behaviour of the alloy and composites produced at various reinforcements were carried out using a Taber abrasion wear-testing machine. The XRF showed the compositions of CHA to contain carbon (95.70 %), silicon (2.60 %), calcium (1.00%) and others. Mechanical properties investigated increase with increase in 3 wt. % to 15 wt. % of CHA. The morphologies revealed uniform distribution of CHA within the matrix resulted to the improvement in both mechanical and wear properties. The wear resistance of the composites increases with increase in the applied load and decreases with increases in the weight percentage of CHA and this can be used in the automobile and engineering industries for the productions of brake shoes, electrical insulators and others.

Keywords: *Aluminum alloy, Cow horn ash, Wear resistance, Microstructure, Mechanical properties, Applied loads*

1. INTRODUCTION

The main aim of material development is to meet the requirement of properties for industrial applications in any industries. Aluminum Metal Matrix Composites (AMMCs) are one such material to provide combination of properties such as high strength, high stiffness, higher thermal conductivity, higher young's modulus and better tribological properties over unreinforced alloys. However, the AMMCs are mostly used in applications such as automobile, marine and aerospace industries [1,2]. Further attempts have been made to improve the mechanical and tribological properties of AMMCs by reinforcing the alloys with synthetic materials such as SiC, B_4C, Al_2O_3, and graphite in order to enhance their wear resistance characteristics [3-5]. Despite their apparent widespread use are not produced in developing countries. The reliance on importation from overseas and the high foreign currency exchange involved implies that the synthetic reinforcements purchased locally are at relatively high cost [6]. Alternative to the high cost of synthetic reinforcers to developing countries currently is to explore some other means such as using wastes from animals and Agriculture. These wastes may be in the form powders or ashes particulates. Ashes and powders obtained from the wastes such as bamboo leaf, rice husk, bagasse, coconut shell, and ground nut shell for the development of AMMCs had been investigated and proved successful in terms mechanical and wear properties improvements [7-9]. These ashes and powders are not just cost effective but the availability and environmentally friendly in nature and had also shown that some of these wastes contain high percentage of refractory materials such as Al_2O_3, silica (SiO_2), hematite (Fe_2O_3) distributed in these wastes [10]. Previous works on the use of agro-wastes as reinforcing fillers in the development of composites had been carried out

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Paper received: 20. 04. 2022.
Paper accepted: 08. 06. 2022.
Paper is available on the website: www.idk.org.rs/journal

by researchers [11-16]. Two body abrasive wear behaviour of Al alloy 1100 composites reinforced by varying the composition of silicon carbide (SiC) at 5, 10 and 20 vol.% were studied and found that abrasive wear resistance of composites increases with increase in vol.% of SiC particles [17]. The mechanical and wear behaviours of Al alloy reinforced with cow horn ash (CHA) composites reinforced by varying the composition of cow horn ash (CHA) at 3-15 at 3 wt.% interval was studied and found that both the mechanical and abrasive wear resistance of composites increases with increase in vol.% of SiC particles [18]. The effect of particle size on abrasive wear behaviour of Al 2024/10 wt.% B_4C composite has been studied and results revealed that the smaller particles of 29 µm has higher abrasive wear resistance compared to larger particles of 71 µm [19]. Effect of both electroless copper coated and uncoated basalt short fibre in Al 7075 Metal Matrix Composites have been investigated and composite with copper coated reinforcement particles showed improved mechanical properties [20]. Investigation of mechanical, microstructure, and wear behaviours of Al-12%Si/reinforced with melon shell ash (MSA) particulates at different weight percent was carried out. The results showed that both the properties investigated were improved [21]. The abrasive wear mechanism on Al AA6061 matrix reinforced with varying wt.% by 5, 10 and 15 of SiC produced by powder metallurgy method was also analyzed. It was found that at low speed, abrasive wear rate is dominated whereas at high speed, delamination was the dominant wear mechanism [22].

Cow horn (CH) is an animal waste by product abundantly available across Nigeria in West Africa. The cow horn is a great environmental threat that can cause damage to the land and the surrounding area in which it is being dumped. Utilization of this waste material could reduce contamination and free up spaces for disposal or recycling of waste materials by converting it into useful material for engineering applications. The effective way of utilizing the cow horn was to convert to ash under controlled burning conditions. Therefore, this research focused on the utilization of cow horn ash (CHA) by dispersing it into the Al-1%Mg-0.6%Si alloy to produce matrix composites through stir casting route. The weight fractions of cow horn ash particles (100 µm) were varied from 0 to 15 %wt. at 3 wt.%. interval in this work. The CHA was characterized by scanning electron microscope attached with energy dispersive spectroscopy (SEM/EDS) to ascertain the compositions. Experiments were conducted to assess the mechanical and wear behaviours of the Al-1%Mg-0.6%Si/0-15 wt.%. (CHSA) composites. Scanning electron microscope (SEM) was used to establish the morphologies of the alloy, composites and wear mechanisms.

2. MATERIALS AND METHODS

2.1 Preparation of cow horn ash

Cow horn ash (CHA) was prepared by cleaning, washing, and drying. After drying, a metallic drum perforated to allow air circulation for combustion to occur was used as burner for the preparation of cow horn ash. The powder was packed in a graphite crucible and fired at temperature range of 400–650 °C for 120 min and removed from furnace after 24 h for proper heat-treatment. This is to allow the reduction of the carbonaceous and volatile constituents of the ash [18]. The ash was ball milled using ball milling machine and sieved to a particle size of 100 µm. The experiment was done at the Department of Agriculture and Bio-resources Engineering, University of Nigeria. Figure 1a and b showed the cow horn collections and the CHA particle size of 100 µm produced respectively.

Figure 1a. Cow horns collection

Slika 1a. Zbirka kravljih rogova

Figure 1b. CHA of particle size 100 µm

Slika 1b. CHA veličine čestica 100 µm

2.2. Equipment

Equipment used in this research are electrical resistance furnace, (scanning electron microscope (SEM), X-ray fluorescent (XRF), and Pin on Disc machine.

2.3. Preparation of Al-Mg%-Si/Corn horn ash particulate composites

The present study utilized aluminium alloy and cow horn ash with a particle size of 100 μm as base matrix and reinforcement, respectively. The chemical composition of the alloy is presented in Table 1. The amounts of cow horn ash (CHA) used as reinforcers were determined using charge calculations presented in Table 2. The aluminium alloy was superheated to 800°C after being charged into a crucible furnace. The stainless-steel stirrer was used to stir the molten alloy/composites manually. The reinforcement particles, CHA, were preheated to 200°C for 30 minutes. After preheating, CHA particles were consolidated into the melt to exclude moisture. To reduce the porosity, the addition of the degassing tablet was added after the alloy/composites were completely melted. The wettability was enriched by the composition of magnesium in the melt. This magnesium improves the wettability between the matrix alloy, reinforcement thus, 3 wt.% to 15 wt.% at 3 wt.% interval by equal CHA proportions used. Preheated moulds were set before casting the alloy and the composite of 30 mm by 100 mm, respectively. Chemical analyses were performed on the alloy and the composite. Figure 2 showed the cast products (alloy/composite) for this research.

Table 1. Al-Mg-Si alloy analysis

Tabela 1. Analiza legure Al-Mg-Si

Compo-sitions	Mg	Si	Fe	Mn	Cr	Cu	Al
Weight percent [wt. %]	1.0	.60	.01	.02	.01	.03	Bal.

Table 2: Summary of charge calculations in weight percent [wt.%]

Tabela 2. Rezime izračunavanja punjenja u težinskim procentima [tež.%]

S/No.	0 wt.% CHA	3 wt.% CHA	6 wt.% CHA P	9 wt.% CHA P	12 wt.% CHA P	15 wt.% CHA
[CHA]	0	3	6	9	12	15
Silicon (Si)	0.600	0.600	0.600	0.600	0.600	0.600
Magnesium	1.000	1.000	1.000	1.000	1.000	1.000
Aluminum	98.400	95.400	92.400	89.400	86.400	83.400
Total	100	100	100	100	100	100

Figure 2. Cast products (alloy/composite)

Slika 2. Liveni proizvodi (legura/kompozit)

2.4. Determination of tensile strength

The tensile tests were carried out on the samples according to ASTM E08-95 at room temperature (30°C), using a universal testing machine (INSTRON). The test was conducted using strain rate of 2mm/min. As cast Al alloy and composites, tensile test specimens were prepared using lathe machine and shaper machine. The specimens were machined to the standard diameter size of 2 mm.

2.5. Determination of the hardness values

The hardness test was carried out using Rockwell hardness machine. The hardness specimen was placed on a flat horizontal stand, with a preload of the diamond cone indenter was used to indent on the surface of the specimen and its hardness value was reflected on a dial gauge of the machine and the readings read from the calibrated C-scale of the gauge as carried out in [18].

2.6. Determination of impact toughness

The impact specimen was placed on a horizontal stand of the Izod Impact Machine. It was arranged such that the notch was directly opposite to the point of impact of a heavily suspended mass. With the gauge set properly, the suspended mass was released from a height to hit the specimen. The energy absorbed by the specimen was reflected on a calibrated scale [20].

2.7. Microstructural examination

The morphologies of the alloys and composites produced were investigated using scanning electron microscope. Samples were polished on emery papers of different grades. The polishing was carried out on a circular cloth pad on its surface. Rough polishing was done using silicon carbide paste and final polishing operation was carried out using alumina polishing paste. Etching of the specimen was carried out using a cotton wool soaked in nital to wipe the specimen's polished surface to give a dull reflection surface [21]. Scanning Electron Microscope (SEM) was used to characterizations the alloy/composites as reported elsewhere [22].

2.8. Wear analysis

Wear test specimen disc of diameter 25 mm and thickness 5 mm was machined from the as-cast produced alloy/composites. The surfaces of each specimen were prepared with 600 grades SiC abrasive papers. A total number of specimens were used for the whole experiment, as for each composition two different loads of 15 and 25N were used. The wear test was carried out on the surface of the specimens using an Anton Paar TRN Tribometer (asper ASTM G99-95 standards). The abrasive medium used was made of stainless-steel ball. An applied load of 15 N and 25 N at 153 rev/min wheel speeds and a dwell time of 3.26 min were used. The sliding speed used was 2 m/s. Weight loss method was adopted to study the wear behaviour. Weight of the specimen before and after each test was measured using digital weigh balance. The mass loss was determined for each specimen by finding the difference between the initial and final mass. Weight loss method was used to calculate the wear rate [18,20].

3. RESULTS AND DISCUSSION

3.1. XRF Analysis of Cow horn ash

The chemical compositions of the CHA are being presented in Figure 3. It could be observed from the figure, that carbon (C) has the highest percentage composition of 95.70 wt.% followed by Si (2.60 wt.%), Ca (1.0) and S (0.7 wt.%), were traces respectively. The analysis also showed that C, Si, Ca are the major constituents while S is the minor element present in the ash. However, the carbon and Silicon played vital roles when used as filler in the aluminum matrix composites for industrial applications. The presence of hard elements like C and Si suggested that, the cow horn ash can be used as particulate reinforcement in various aluminium metal matrixes according the previous findings [18,19].

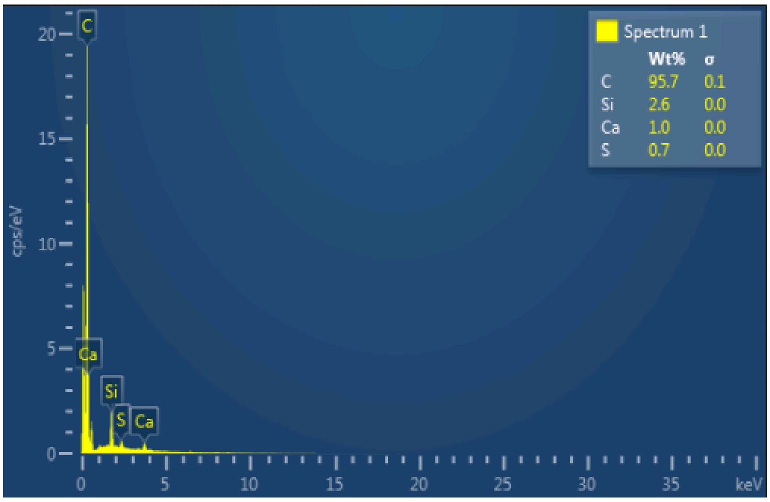

Figure 3. SEM/EDS of Cow horn ash (CHA)

Slika 3. SEM/EDS pepela od kravljeg roga (CHA)

3.2. The morphologies of the alloy/composites

From Figure 3 presented, it is obvious that the wear rate of the Al-Mg-Si/cow horn ash particle composites increases when the load was changed from 15N to 25N. Wear resistance increases with the increase in cow horn ash content. This may be attributed to the fact that cow horn ash particles act as hard solid particles and improve the wear resistance. From the morphologies presented, the least weight loss occurs in the composite containing 15 wt.% reinforcement of CHA, while the highest weight loss was observed for the unreinforced Al-Mg-Si alloy. This is also similar to the findings of [22,23].

The Figure 3 revealed the same trend with more volumes of light black portions to deep black portions of compounds formed such as calcium silicate ($CaSiO_4$), silica (SiO_2). It was found out that there was good bonding between Al matrix and the filler (CHA) particles and no gap was observed between the particle and matrix as being shown in Figure 4 (b, c & d), respectively. There was good retention and good interfacial bonding of cow horn ash particles in the composites with different weight percentage of reinforcers. Addition of small quantities of magnesium during stirring also improved the wettability of cow horn ash particles and in agreement with the previous works [24,25].

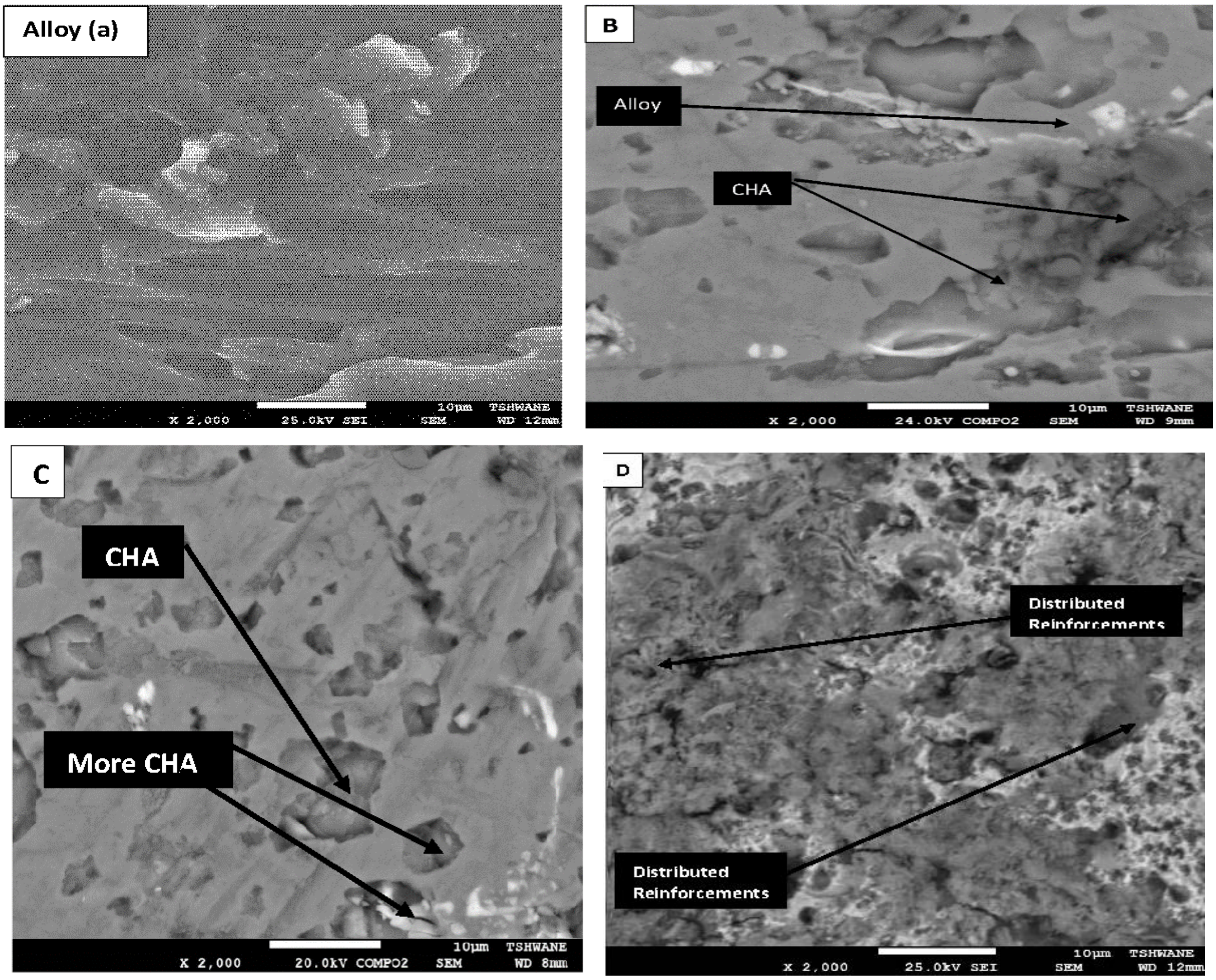

Figure 4. SEM morphologies of aluminium alloy/composites at (a), 9 wt.% CHA (b) 12 wt.% CHA at (c) and 15wt.% CHA at (d)

Slika 4. SEM morfologije legure aluminijuma/kompozita na (a), 9 tež. .% CHA (b) 12 tež.% CHA u (c) i 15 tež.% CHA u (d)

3.3. Mechanical Properties of Alloy/Composites

3.3.1. Hardness Values

The hardness, tensile strength, impact toughness and percentage elongation of the alloy and the composites were presented in table 3 and Figure 4 respectively. The hardness value of the alloy was 49.77 HRC increased to 88.6 HRC at 15 wt.% CHA. That is an increase of 43.83% of the alloy to the composite at 15 wt.% CHA was recorded. Previous works attributed this increase in hardness to the increase in the particle size and specific surface of the reinforcement for a given volume fraction [26]. The hardness values were improved at higher wt.% of CHA loading. The improvement of the hardness of the composites to the increased particle volume fraction, and increased strain energy at the periphery of particles dispersed in the matrix confirmed the previous studies [26].

3.3.2. Tensile Strength

The alloy/composite with cow horn ash results is also being presented in Figure 4. The addition of cow horn ash particles significantly improved the tensile strength of the composites compared to the alloy. The improvement observed in tensile strength of the composite was attributed to the fact that the corn horn ash acts as filler and possesses higher strength which was more resistance [26]. The cow horn ash contains ceramic materials, such as C, Ca, Si, etc. which had a favourable combination of density; the hardness exhibits a significant increase in its elastic modulus, hardness, strength and wear resistance, accordingly to the findings of [27, 28]. Hence, improvement in the strength of the composites can be explained by the presence of ceramic particles in the cow horn ash. It was therefore estimated that about 45.23 % increase in the tensile strength from 0 wt. % to 15 wt.% CHA respectively.

3.3.3. Elongation

The percentage elongation is shown in Figure 5. It increases from 0 wt.% to 15 wt% of CHA. However, at the particle size (100 µm) of the filler due to high surface area and good wettability, the porosity of the composite decreases, which give rise to high strength at low percentage from 3 wt.% to 15 wt.% of the filler in the matrix [27, 28].

3.3.4. Impact Toughness

The toughness result in Figure 4 also show an increase from 0 wt.% to 15 wt.% CHA. This can be attributed to particle and interfacial cracking in the reinforcements. The toughness values became virtually constant from 3 wt.% to 15 wt.% CHA and similar to the reports of [26].

Table 3. Values of the mechanical properties studied

Tabela 3. Vrednosti proučavanih mehaničkih svojstava

Wt. % CHA	Hardness [HRC]	Tensile stress [MPa]	Impact test [J]	Percentage elongation [%]
0	49.77	63	26	9.6
3	70	90	29	15.4
6	84.9	98	33.5	20.3
9	87	104	36	21.7
12	88	110	37	22.6
15	88.6	115	38	23.5

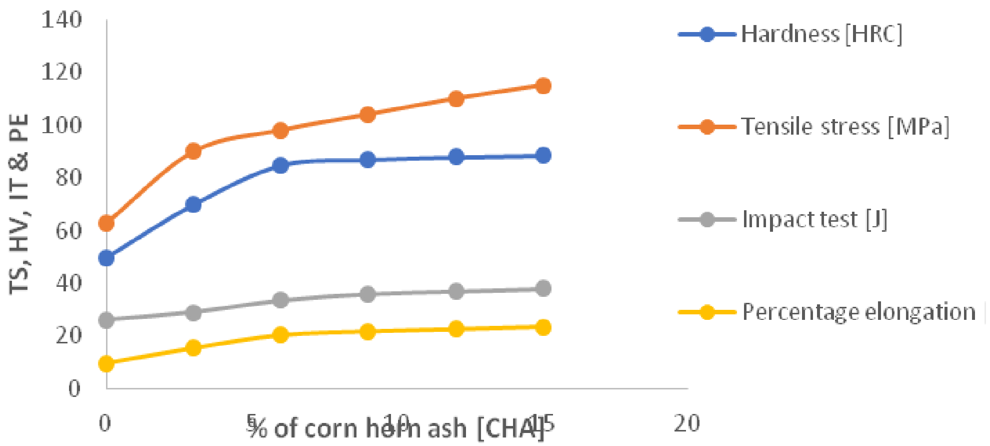

Figure 5. Variations of tensile, hardness, impact and elongation of Alloy and composites against wt.% CHA

Slika 5. Varijacije zatezanja, tvrdoće, udarca i izduženja legure i kompozita u odnosu na mas.% CHA

3.4. Wear properties of composite

Wear can be described as the gradual loss of materials due to relative motion between a surface and the contacting substance and this may be in the form of micro-cracks or localized plastic deformation as reported by previous finding [17,21]. The results of the wear rate against the reinforcements of the cow horn ash (CHA) and SEM were being presented in Figures 6 and 7 respectively. From the figures, it was observed that the wear rate decreases with increased in the weight percentage of cow horn ash particles. It is obvious that the composites exhibited significantly higher wear resistance than the Al-Mg-Si alloy due to the addition of cow horn ash which has higher carbon, calcium, silicon that might acted as a load bearing constituent. As the percentage of cow horn ash content increases, the wear rate of the composite decreases. An increase in cow horn ash in the composite restricts deformation of the matrix material with respect to load. Hence, the wear rate for the increase in CHA content composite is decreasing according to Figure 5 and similar to the previous works of [29,30]. However, Figure 6 showed the SEM morphologies of Al-Mg-Si and the composites at 15 wt.% CHA).

It is observed that material removal of the prepared specimens occurred through micro cutting and micro chipping process only. Wide range of abrasion (ploughing) marks are seen on the surface of the prepared composite specimen and no deeper cuts took place during the wear process when compared with the unreinforced alloy of Al-Mg-Si. The morphology appears rough and irregular thus displaying good bonding with the matrix. This is similar to the claims of [21,24,30].

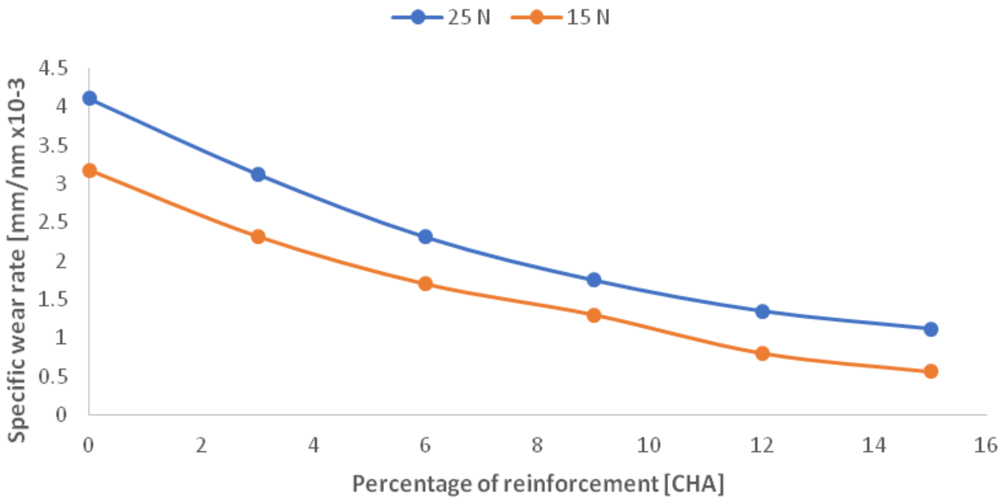

Figure 6. Effect of reinforcement on specific wear rate

Slika 6. Uticaj armature na specifičnu brzinu habanja

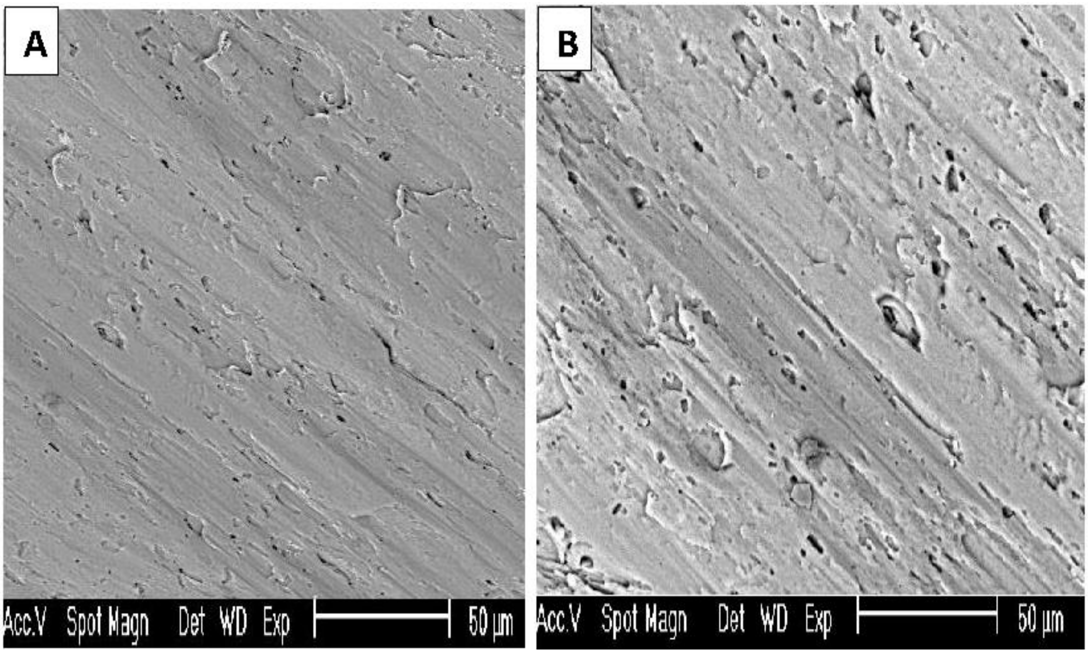

Figure 7. SEM morphology of Al-Mg-Si alloy (a) without load (b) reinforced with 15 wt.% CHA particles at applied loads

Slika 7. SEM morfologija Al-Mg-Si legure (a) bez opterećenja (b) ojačane sa 15 tež.% CHA čestica pri primenjenim opterećenjima

4. CONCLUSIONS

The mechanical and wear resistance of the unreinforced alloy and reinforced by cow horn ash has been described. Hence, the following conclusions have been drawn from the results:

- The mechanical properties described showed that the reinforcements of CHA had improved the properties of the composites favourably.
- Morphologies clearly revealed that the composites materials produced by stir casting

method showed no voids and discontinuities of CHA particulates in the matrix which resulted in sound castings.

- The wear rate behaviour dependents on the hardness of the composite and the wear rate of the composite decreased from Al-Mg-Si to Al-Mg-Si/15 wt.% CHA).
- The morphologies of the wear rate of the alloy and the composites revealed that the material removal was mainly due to micro cutting.
- CHA being an animal waste was a good substitute to imported reinforcers such as Al_2O_3, TiC, SiC, and B_4C which are available, cheap and environmentally friendly.

Acknowledgements

The authors are thankful to the technical staff of Department of Metallurgical and Materials Engineering laboratory, University of Nigeria, Nsukka and Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa, Main Campus Pretoria West.

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IZVOD

Poboljšanje mehaničkog ponašanja i trošenja ojačane legure aluminijuma sa česticama pepela životinjskog porekla

Istraživački rad je ispitivao mehaničko ponašanje i habanje legura aluminijuma ojačanih pepelom od kravljeg roga (CHA) koji je isplativ i ekološki prihvatljiv materijal u različitim težinskim procentima (0 tež. % do 15 tež. %) pri 3 tež. % interval. Pepeo od kravljeg roga je okarakterisan rendgenskom fluorescencijom (KSRF). Morfologija matrice i kompozita proučavani su pomoću skenirajućeg elektronskog mikroskopa (SEM) za distribuciju čestica pepela kravljeg roga unutar matrice. Ponašanje na habanje legure i kompozita proizvedenih na različitim armaturama je sprovedeno korišćenjem Taber mašine za ispitivanje habanja. KSRF je pokazao da sastav CHA sadrži ugljenik (95,70%), silicijum (2,60%), kalcijum (1,00%) i druge sastojke. Ispitivane mehaničke osobine rastu sa povećanjem od 3 tež. % do 15 tež. % CHA. Morfologije su otkrile ujednačenu distribuciju CHA unutar matrice što je dovelo do poboljšanja i mehaničkih i habajućih svojstava. Otpornost na habanje kompozita raste sa povećanjem primenjenog opterećenja i opada sa povećanjem težinskog procenta CHA i to se može koristiti u automobilskoj industriji i industriji za proizvodnju kočionih papučica, električnih izolatora i dr.

Ključne reči: *legura aluminijuma, pepeo od kravljeg roga, otpornost na habanje, mikrostruktura, mehanička svojstva, primenjena opterećenja*

Naučni rad

Rad primljen: 20. 04. 2022.

Rad prihvaćen: 08. 06. 2022.

Rad je dostupan na sajtu: www.idk.org.rs/casopis