Journal of Bio- and Tribo-Corrosion (2021) 7:72
https://doi.org/10.1007/s40735-021-00510-x

Corrosion Behaviour of Bamboo Leaf Ash-Reinforced Nickel Surface-Deposited Aluminium Metal Matrix Composites

Nitla Stanley Ebenezer[1] · B. Vinod[2] · Hanumanthu Satya Jagadesh[3]

Received: 16 December 2020 / Revised: 4 March 2021 / Accepted: 28 March 2021 / Published online: 8 April 2021

Abstract

The global consumption of bamboo leaves behind with greater amounts of waste leaves occupies a majority of landfills. Burning of this residual debris (bamboo leaves) in an unrestrained manner poses out multiple adverse and irreversible effects on both human and the environment we live in. A large number of residual wastes are being generated through industrial and agricultural operations due to the forever increasing world population. These residual debris is often involving much complicated processes for disposal. Converting the stubborn residual debris to green material systems is regarded as optimal and effective way for the current pollution crisis. The current study mainly intends for the use of calcined ash from bamboo waste leaves which have a tremendous pozzolanic properties and can be used as natural industrial-agro filler and inspecting the corrosion behaviour of nickel-deposited aluminium–bamboo leaf ash composites. The base A356.2 aluminium alloy is reinforced with bamboo leaf ash particulates by employing stir casting technique varying the reinforcement percentages, i.e. 2, 4 and 6 wt. %. The fabricated Al-BLA composites are nickel electrodeposited with a customary watt's bath. The corrosion behaviour of the test samples is investigated thoroughly by employing polarization tests under aerated 3.5% Nacl ambience. The microstructural and coating surface morphology is studied by employing SEM and XRD practices. It was noted the nickel-deposited Al-BLA composites flaunted enhanced corrosion resistance and elevated mechanical behaviour upon increasing the percentage of the reinforcement.

Keywords Aluminium metal matrix composites · Agro-reinforcement · Bamboo leaf ash · Corrosion · Nickel surface deposition

1 Introduction

The harsh and detrimental consequences caused due to the accumulation of industrial-agro waste products entice several research fanatics for exploring recent techniques for restraining environmental deterioration. Recently, researchers and industrialists are mostly focused on exploring industrial-agro by-products as an environmentally sound and efficient replacement for the high-cost, scarcely avail reinforcements [1, 2]. Although other reinforcements like SiC, Al_2O_3, B_4C, TiB_2, TiC, and graphite rendering enhanced mechanical, thermal, wear, and corrosion resistance are often limited their usage because of their higher toll in price due to their scarce availability and complicated manufacturing routes [3, 4]. Development of eco-friendly, low-cost, low weight are available aluminium matrix systems with exceptional mechanical behavioural traits have been researched intensively. Recent works include reinforcing the matrix core system with silica-enriched industrial and agricultural by-products like coconut shell ash, rice husk ash, red mud and bamboo leaf ash, which are found operational in replacing the conventional high-cost reinforcements [5–7]. Among all the low-cost agro reinforcements, bamboo is one of the fastest-growing, abundantly available, and highest yielding natural resources known to mankind since ages intended for numerous applications. According to world estimates, nearly 20 million tons of bamboo is been utilized for various applications. However, this would be creating the

✉ Nitla Stanley Ebenezer
stanxaviers@gmail.com

1 Department of Mechanical Engineering, Aditya College of Engineering and Technology, Surrampalem 533437, India

2 Department of Mechanical Engineering, Priyadarshini College of Engineering and Technology, Nellore 524004, India

3 Department of Mechanical Engineering, GITAM Deemed to be University, Visakhapatnam 530045, India

Table 1 Percentage chemical constitution of base A356.2 alloy

Si	Fe	Cu	Mn	Mg	Zn	Ni	Ti
6.5–7.5	0.15	0.03	0.10	0.4	0.07	0.05	0.1

Table 2 Percentage chemical constitution of BLA

Constituent	Silica	Alumina	Calcium oxide	Magnesium oxide	Potassium oxide	Ferric oxide
%	75.90	4.13	7.47	1.85	5.62	1.22

accumulation of higher volumes of solid wastes (bamboo leaves) covering the majority of landfills and the uncontrolled burning of the residual wastes leading to hazardous environmental issues [8]. From the previous studies, it is well aware that reinforcing the matrix system with agro reinforcements witnessed improved mechanical, damping, and tribological characteristics. The type of agro-reinforcement employed, volume fraction, processing route and shape of the ago-reinforcement employed resulted in tailoring several properties of the composite [9–12].

Traditional metals, non-metals and composites interact with adverse environments and are influenced by various external actions which may eventually cause some serious effects on the material's life. Corrosion is often dubbed as an adherent degenerative phenomenon that progressively deteriorates the material's life due to various chemical and physiological influences. According to NACE (National Association of Corrosion Engineers), it is estimated that the corrosion costs were US$276 billion in 1998, and the global corrosion costs for the year 2016 were summed up to US$2.5 trillion. Besides, corrosion poses a serious threat to the depletion of natural resources by trying to replace the corroded materials [13, 14].

The surface of a material is most vulnerable to chemical, mechanical electrical, and thermal actions. In order to protect the material's superficial surface, various surface treatments are employed. Coatings are thin layers casing the substrate material mostly post-processing techniques intended for enhancing the appearance, functioning, and life of the substrate [15–17]. Coatings may be applied to few parts of the substrate or totally covering the substrate. The various types of coating techniques like chemical vapour deposition, conversion coating, plasma spraying, electroplating and electroless plating are effectively implemented for effective usage and extending the materials life [18]. Among the several surface deposition practices, electrolytic and electroless surface metal depositions are often labelled as the utmost simplified and inexpensive techniques. The nickel surface deposition mostly aspires in enhancing the mechanical behaviour, aesthetics and preventing the metal substrate from corrosion and wear deterioration. Electrosurface deposition involves smooth and faster metal deposition in comparison with electroless deposition. Moreover, achieving the finest nickel is only possible through electrodeposition [19].

Table 3 Stir casting details

S. No	Stirring speed	Stirring temperature	stirring time	blade angle
1	600–700 rpm	750–800 °C	5–10 min	45 and 60 °C

Henceforth, the current study chiefly focussed on developing an eco-friendly, low-cost, highly available material system. Furthermore, from the existent literature, it is noticeable that there is some sparsity regarding the bamboo leaf ash composites. No previous works have been reported on the corrosion characteristics of the nickel surface-deposited BLA composites. Therefore, the current study endeavours for determining the corrosion behaviour of nickel surface-deposited Al-BLA composites by engaging potentiodynamic polarization curves.

2 Experimentation

2.1 Fabrication of Agro-Reinforced Composite:

In the existent study, A356.2 alloy and bamboo leaf ash of particle size of 25 µm are employed as the matrix and reinforcement materials. The individual element constitution of the duo is presented in Tables 1 and 2. The aluminium bamboo leaf ash composites are processed by engaging universal stir casting practice at three dissimilar weight percentages viz. 2, 4 and 6% in a strict argon gas ambience. The details of stir casting are represented in Table 3.

Initially, A356.2 aluminium alloy with theoretical density 2760 kg/m^3 is heated to 750 °C in a graphite crucible till the entire metal reaches to a molten state. Degassing tablet is then added to the molten metal for reducing porosity. Coincidentally, 1 wt. % magnesium is added for enhancing the wettability between BLA and A356.2 alloy. It is even observed that in the absence of magnesium, BLA particles outcaste from mixing up with the aluminium alloy. A stainless stirrer is lowered into the liquid metal and is stirred at speeds between 500 and 700 rpm [20]. The stirrer speed is typically controlled with a regulator equipped on the furnace.

Before incorporating the reinforcing phase, the bamboo leaf ash particles are heat treated about 350 °C in a muffle furnace for eliminating the moisture, impurities contained within BLA. Pre-treatment of BLA enables easy and stable diffusion of the filler material into the core matrix system. The preheated BLA particles are embedded into the liquid metal at a steady rate and at a continual stirring time [21]. The stirring action is performed for an additional 5 min after the incorporation of the reinforcing material. The resultant aggregation is coursed into a preheated mould at a temperature of 500 °C for 35 min. Using this technique, 2, 4 and 6 wt. % by weight BLA-reinforced composites are synthesized according to the ASTM standards B26/B26M-09. The base alloy and reinforcement are acquired from Balco/Vedanta native retailer.

2.2 Nickel Deposition

The synthesized Al-BLA composites are nickel surface deposited by engaging a classically stirred watts electrolytic bath consisting of the following chemical ingredients as shown in Table 4. Prior to the immersion in the aqueous solution, the test samplings are cleaned thoroughly using sulphuric acid and polishing for better adhesion. Following this, the test samples are dipped in zinc bath for almost 30 s [22]. In order to achieve the desired surface deposition, several trails have been made fluctuating the current densities. In the current case, an optimal uniform deposition has occurred at a 20 A/dm^2 current density.

2.3 Corrosion Testing

The corrosion behaviour of the Al-BLA composites is assessed by engaging an electrochemical-based software system (Gill AC). This electrochemical system equips reference electrode which is saturated calomel electrode (SCE) and an auxiliary electrode as carbon electrode. The experimentation is initiated at a starting potential of – 0.25 V (OC) SCE until the concluding potential is reached. The entire polarization trails have been carried at a rate of 0.166 mV s-1 in 3.5% NaCl aerated ambience [23]. The test samples' contact region is taken as 1 cm^2. The temperature of the cell unit is regulated with a thermocouple, the dissolved oxygen content is regulated by incorporating argon inert gases. Similarly, the concentration of pH and ambient chemistry are carefully monitored for the entire corrosion investigation process. The corrosion potential is Ecorr is often treated as the convergence occurring between the branches of the duo, i.e. cathode and anode.

Table 4 Nickel surface deposition chemical constituents

Composition	Conditions
Nickel sulphate ($NiSO_4.6H_2O$)	240 gl^{-1}
Nickel chloride ($NiCl_2$. $6H_2O$)	35 gl^{-1}
Boric acid (H_3BO_3)	30 gl^{-1}
pH of solution	4
Deposition temperature	60 °C
Plating time	20 min
Current density	20 Am^{-2}

3 Results and Discussion

3.1 Microstructural Characterization

From Fig. 1, it is evident obvious that bamboo leaf ash particulates of dissimilar orientations are finely embedded into the matrix core system. Henceforth, the stir casting route is effective in synthesizing the Al-BLA composites. The existence of reinforcement particulates into the core system depicts a crucial part in enhancing the material properties [24]. Figure 2 indicates cross section of the surface-deposited nickel test specimen indicating a uniform surface coat throughout the length. From the surface morphology characterization, it is apparent that a smooth even nickel coat is achieved free from cracks and blemishes.

3.2 Adhesion, Hardness, and Residual Stresses

Nano-scratch analysis is engaged for determining the adherence properties of the surface-deposited composites preceding and seceding the heat treatment. The nano-scratch test is carried out by employing a 4.4 mm diameter stylus and at loading of 50 nm. The results stated that nickel surface-deposited test samplings offered optimal adherence

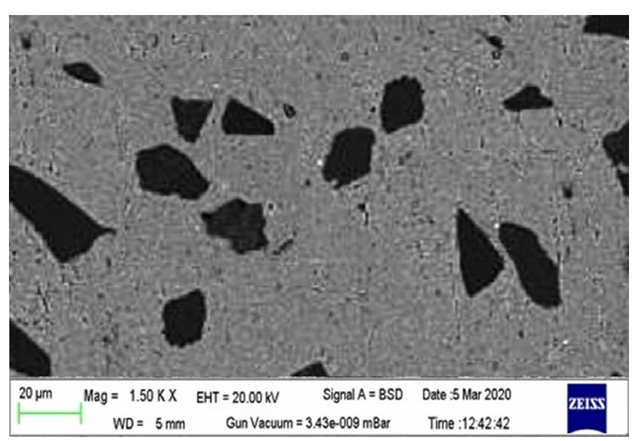

Fig. 1 SEM photomicrographs 6% Al-BLA composites

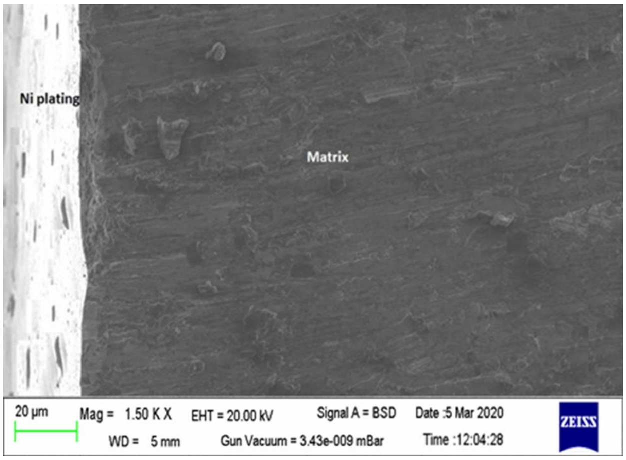

Fig. 2 Cross-sectional SEM image of nickel surface deposition

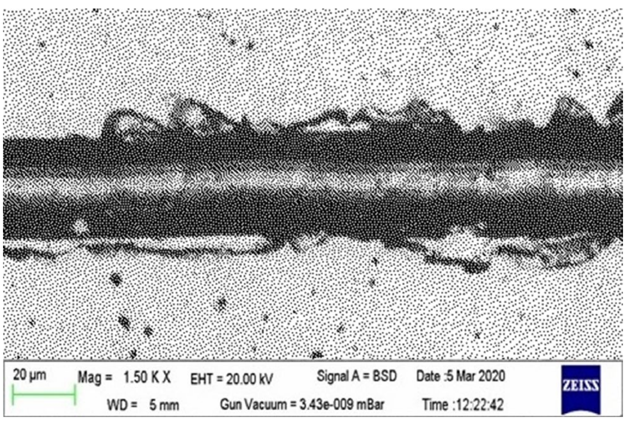

Fig. 3 SEM photomicrographs of scratch test of nickel surface-deposited alloy

characteristics with no visible signs of debonding and blemishes. The SEM photomicrographs after nano-scratch test are depicted in Fig. 3, flaunting the superior adherence onto the aluminium substrate with minimal flaking of the nickel deposit due to refined grain structure [25]. The nickel surface-deposited test rendered an average hardness of 356 HV. The residual stresses acting on nickel-deposited test samplings are minimal falling in the range of 72–79 MPa and are primarily of compressive in nature. The tough processing conditions and the apt chemical constituents engaged for nickel deposition resulted in minimal residual stresses.

3.3 Corrosion Behaviour

Figure 4 depicts the polarization plots base alloy and nickel surface-deposited alloy. From the plots, it is evident that corrosion potential (E_{corr}) for the base aluminium alloy and nickel surface-deposited alloy is − 340 mV and − 260 mV.

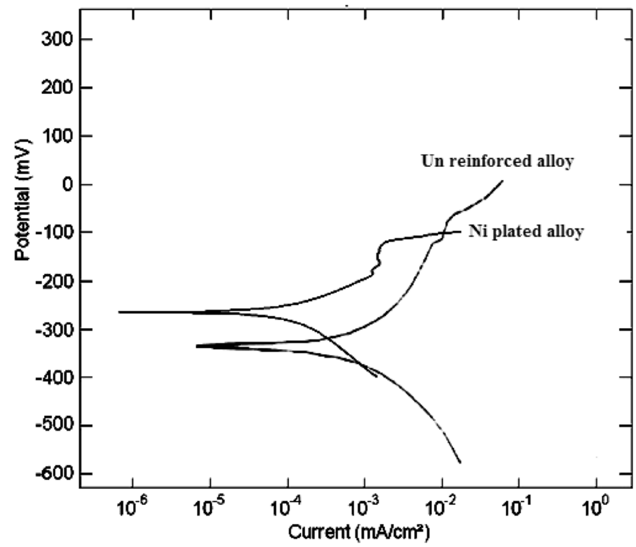

Fig. 4 Potentiodynamic polarization plots for base alloy and nickel surface-deposited base alloy

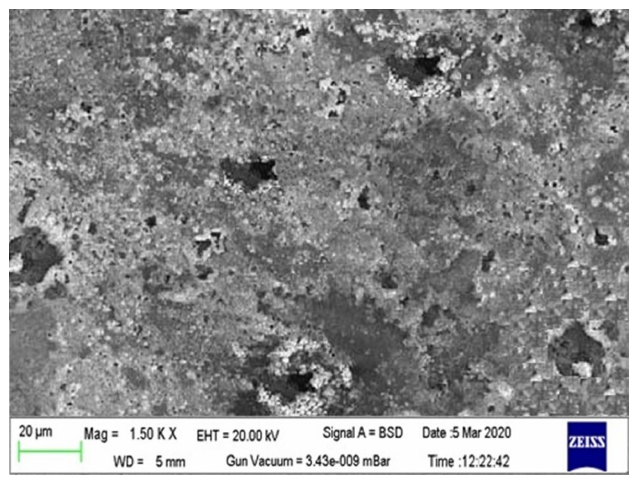

Fig. 5 SEM photomicrographs of A356.2 alloy Ni surface-deposited base alloy succeeding the polarization tests

Nickel surface-deposited alloy flaunted higher positive potentials in comparison with untreated aluminium alloy which resembles an enhanced thermodynamic stability of the surface-deposited alloy. From the plots, it is further evident that the surface-deposited alloy yielded much lesser current densities when compared to the untreated base alloy. The minimal current densities restricted the mobility of the constituent elements thereby curbing the corrosion deterioration. The fine continual nickel deposit on the substrate acts as a protective layer there by preventing the substrate peripheral surface from degradation due to the corrosive ambiance [26]. Figure 5 depicts SEM photomicrographs of the base aluminium alloy and the nickel surface-deposited alloy preceding and succeeding the polarization trails. From the photomicrographs, it is evident that the untreated base alloys witness maximal corrosion deterioration with higher, wider, deeper amounts of pits and cracks.

Figure 6 illustrates the polarization plots of the for the aluminium bamboo leaf ash-reinforced composites. From the plots, it is evident that corrosion potentials for the nickel surface-deposited 2, 4 and 6% bamboo leaf ash composites are − 395, − 357 and − 267 mV. It can be noted from the plots that with the increased percentage of dispersoid content yielded in higher positive potentials, i.e. 6% reinforcement flaunted the highest positive potential when compared with 4% having the second highest potential and 2% having the least positive potential. From tafel plots, it is apparent that the test samplings with the incrementing reinforcement percentage witnessed minimal current densities. For most particulate-reinforced composites, corrosion deterioration mainly nucleates at the sites of intermetallic phase arising between the matrix and reinforcement systems mainly due to the grain boundary dislocations, interfacial slips and other surface defects. These surface defects nucleating at the cites of matrix-particulate systems act at the epicentres for the nucleation of localized corrosion which intensifies periodically. In order to prevent this, a uniform adherent nickel coat is deposited on the substrate surface Al-BLA composites. In the current study, it is evident that ample amounts of nickel layers are deposited across the dislocations, surface defects arising among the matrix and reinforcement interphases thereby acting as a potential barrier against corrosive degradation. However, the generous amounts of nickel deposition might have decelerated the arising particulate-matrix dislocations thereby enhancing the corrosion resistance. The elevated corrosion resistances upon increase in the percentage of dispersoid contents can be accounted for increased dislocations, refined grain structure and grain boundary defects nucleating at the vicinity metallic interfaces where optimal layers of nickel have been deposited. The surface-deposited yielded a fine, continual and adherent layer on substrate with no traces of flaking shaping up a distinctive core system which acts as surface barrier against the corrosion deterioration.

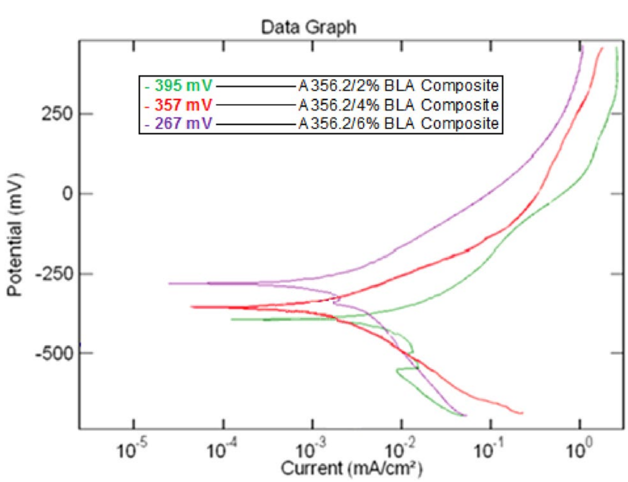

Fig. 6 Potentiodynamic polarization plots for nickel surface plated **a** − 395 mV/A356.2/2%, **b** − 357 mV/A356.2/4%, **c** − 267 mV/A356.2/6% of Al-BLA composites

Figure 7 indicates the SEM photomicrographs of Al-BLA-reinforced composites after corrosion tests. From the photomicrographs, it is obvious that the surface consists of micro-cracks pits and voids, denoting localized corrosion of the surface-deposited Al-BLA composites. It is further noted that the intensity, rate and depth of pits and cracks are minimized upon the increasing dispersoid percentages.

The XRD spectrum of the nickel surface-deposited alloy is depicted in Fig. 8. It is obvious that the surface of deposition with nickel on the substrate materials nucleated a superior Ni_3Al intermetallic [27]. These novel nucleated intermetallic phases have played a prominent role in elevating the corrosion resistances to a greater extent. From the prior literature, it is well known that the Al-Ni intermetallic phases have a distinctive presence in elevating the mechanical, damping and wear and corrosion resistances [28, 29]. The nucleation of the stable Ni_3Al involves dissolution of the constituent nickel to aluminium followed by confined saturations and persistent diffusions of nickel. The presence of coherent and thermally stable Ni_3Al intermetallic phases tends to elevated the corrosion resistance to maximal extent thereby protecting the substrate surface of degradation the corrosive ambience. Novel Al-BLA composites have been successfully fabricated through stir casting route and the unique nickel electrodeposition enhanced the corrosion resistance to maximal extents.

4 Conclusions

From the abovementioned findings, the resulting inferences can be made. By engaging classic stir casting route, aluminium–bamboo leaf ash composites are successfully synthesized.

- A homogenous nickel layer is effectively surface deposited into the alloy and Al-BLA composites.
- The microstructural characterization confirms the existence of bamboo leaf particulates in the core matrix. From the potentiodynamic polarization curves, the corrosion resistance of the nickel surface-deposited BLA-reinforced composites has been enhanced drastically in contrast to the unreinforced base alloy.
- It is evident that the corrosion deterioration is minimized with effective nickel surface deposition onto the com-

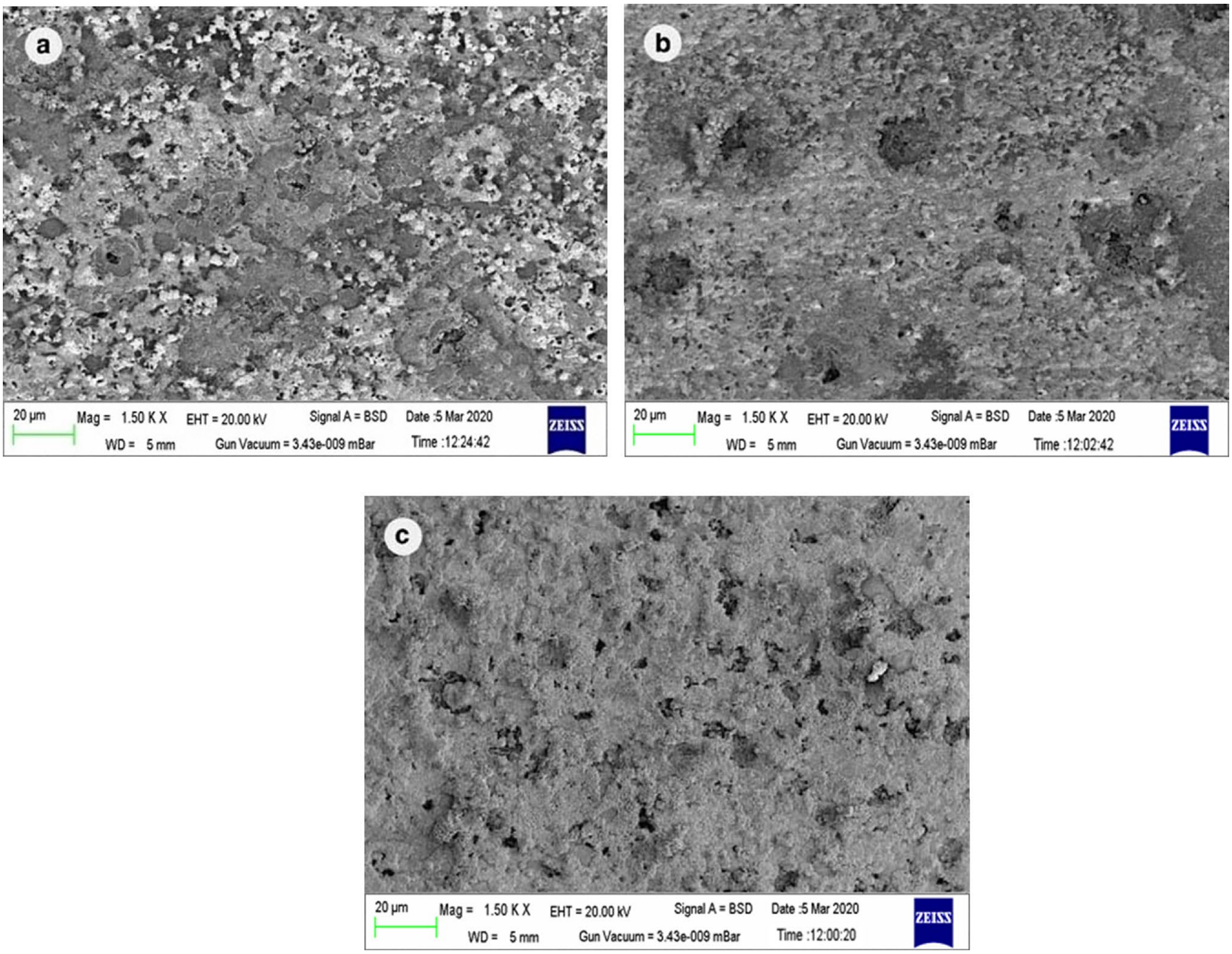

Fig. 7 SEM photomicrographs for nickel surface plated **a** 2%, **b** 4%, **c** 6% Al-BLA composites preceding polarization tests

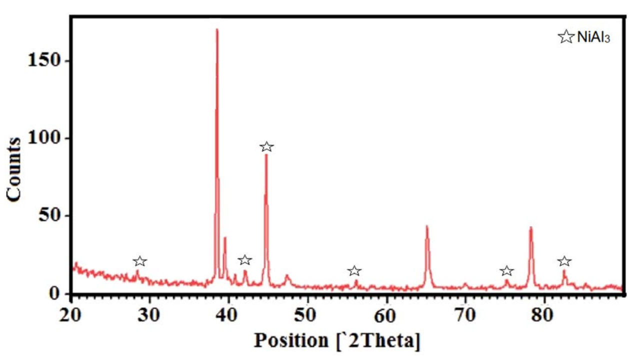

Fig. 8 XRD spectrum of nickel surface-deposited 4% Al-BLA composites

posite substrates and with the increase in reinforcement percentage.

- Therefore, it can be concluded that nickel surface-deposited bamboo leaf ash composites can be effectively employed as reinforcement aluminium metal matrix composites for attaining maximal corrosion resistance.
- The higher corrosion resistance endured due to nickel electrodeposition reduces maintain and investments expenditures thereby enhancing the material's life.
- The future of nickel deposits seems to be vivid in most aerospace, marine and automobile where high corrosion resistance materials are of utmost importance. Incorporation of composite materials through electrodeposition can impact the fabrication of high corrosion-resistant materials.

Declarations

Conflict of interest The author declares that there is no conflict of interest.

References:

1. Muthazhagan, C., Gnanavelbabu, A., Rajkumar, K. and Bhaskar, G.B., 2014. Corrosion behavior of Aluminium-Boron carbide-Graphite composites. In Applied Mechanics and Materials (Vol. 591, pp. 51–54). Trans Tech Publications Ltd.
2. Alaneme KK, Bodunrin MO (2011) Corrosion behavior of alumina reinforced aluminium (6063) metal matrix composites. J Minerals Mater Characterization Eng 10(12):1153–1165
3. Ramalingam VV, Ramasamy P (2017) Modelling corrosion behavior of friction stir processed aluminium alloy 5083 using polynomial: radial basis function. Trans Indian Inst Met 70(10):2575–2589
4. Zakaria HM (2014) Microstructural and corrosion behavior of Al/SiC metal matrix composites. Ain Shams Eng J 5(3):831–838
5. Abd El-Aziz K, Saber D, Sallam HEDM (2015) Wear and corrosion behavior of Al–Si matrix composite reinforced with alumina. J Bio-and Tribo-Corrosion 1(1):5
6. Shanmughasundaram P, Subramanian R, Prabhu G (2011) Some studies on aluminium–fly ash composites fabricated by two step stir casting method. Eur J Sci Res 63(2):204–218
7. Alaneme KK, Ajayi OJ (2017) Microstructure and mechanical behavior of stir-cast Zn–27Al based composites reinforced with rice husk ash, silicon carbide, and graphite. J King Saud Univ-Eng Sci 29(2):172–177
8. Sambathkumar M, Navaneethakrishnan P, Ponappa KSKS, Sasikumar KSK (2017) Mechanical and corrosion behavior of Al7075 (hybrid) metal matrix composites by two step stir casting process. Latin American Journal of Solids and Structures 14(2):243–255
9. Dhadsanadhep, C., Luangvaranunt, T., Umeda, J. and Kondoh, K., 2017. Fabrication of Al/Al 2 O 3 composite by powder metallurgy method from aluminum and rice husk ash. Journal of metals, Materials and minerals, 18(2).
10. Kumar KR, Pridhar T, Balaji VS (2018) Mechanical properties and characterization of zirconium oxide (ZrO2) and coconut shell ash (CSA) reinforced aluminium (Al 6082) matrix hybrid composite. J Alloy Compd 765:171–179
11. Raju RSS, Panigrahi MK, Ganguly RI, Rao GS (2019) Tribological behaviour of al-1100-coconut shell ash (CSA) composite at elevated temperature. Tribol Int 129:55–66
12. Ebenezer NS, Narayana PS, Ramakrishna A (2020) Mechanical and microstructural characterization nickel electroplated metal matrix composites. Materials Today: Proceedings 27(2):1278–1281
13. Surappa MK (2008) Dry sliding wear of fly ash particle reinforced A356 Al composites. Wear 265(3–4):349–360
14. Alaneme KK, Olubambi PA, Afolabi AS, Bodurin MO (2014) Corrosion and tribological studies of bamboo leaf ash and alumina reinforced Al-Mg-Si alloy matrix hybrid composites in chloride medium. Int J Electrochem Sci 9(10):5663–5674
15. Kala H, Mer KKS, Kumar S (2014) A review on mechanical and tribological behaviors of stir cast aluminum matrix composites. Procedia Materials Science 6:1951–1960
16. Ramachandra M, Radhakrishna K (2005) Synthesis-microstructure-mechanical properties-wear and corrosion behavior of an Al-Si (12%)—Flyash metal matrix composite. J Mater Sci 40(22):5989–5997
17. Di Bari GA (2000) Electrodeposition of nickel Modern Electroplating 5:79–114
18. Prasad DS, Ebenezer NS, Shoba C (2017) The effect of nickel electroplating on corrosion behavior of metal matrix composites. Trans Indian Inst Met 70(10):2601–2607
19. Deqing W, Ziyuan S, Tangshan K (2005) Composite plating of hard chromium on aluminum substrate. Surf Coat Technol 191(2–3):324–329
20. Hamdy AS, Shoeib MA, Hady H, Salam OA (2007) Corrosion behavior of electroless Ni–P alloy coatings containing tungsten or nano-scattered alumina composite in 3.5% NaCl solution. Surf Coat Technol 202(1):162–171
21. Khajuria A, Akhtar M, Pandey MK, Singh MP, Raina A, Bedi R, Singh B (2019) Influence of ceramic Al_2O_3 particulates on performance measures and surface characteristics during sinker EDM of stir cast AMMCs. World J Eng 16(4):526–538
22. Aruna ST, Grips VW, Rajam KS (2009) Ni-based electrodeposited composite coating exhibiting improved microhardness, corrosion and wear resistance properties. J Alloy Compd 468(1–2):546–552
23. Srivastava M, Selvi VE, Grips VW, Rajam KS (2006) Corrosion resistance and microstructure of electrodeposited nickel–cobalt alloy coatings. Surf Coat Technol 201(6):3051–3060
24. Pal S, Bhadauria SS, Kumar P (2019) Pitting corrosion behavior of F304 stainless steel under the exposure of ferric chloride solution. J Bio-and Tribo-Corrosion 5(4):1–3
25. Alizadeh M, Cheshmpish A (2019) Electrodeposition of Ni-Mo/Al2O3 nano-composite coatings at various deposition current densities. Appl Surf Sci 466:433–440
26. Rezaei M, Jeshvaghani RA, Shahverdi HR, Mojaver R, Torkamany MJ (2017) Formation of Ni-rich aluminide layers on an A356 aluminum alloy by a combined electroplating/laser alloying treatment: Microstructure and tribological characteristics. J Manuf Process 29:310–319
27. Khajuria A, Akhtar M, Bedi R, Kumar R, Ghosh M, Das CR, Albert SK (2020) Influence of boron on microstructure and mechanical properties of Gleeble simulated heat-affected zone in P91 steel. Int J Press Vessels Pip 188:104246
28. Khajuria A, Kumar R, Bedi R (2019) Effect of boron addition on creep strain during impression creep of P91 steel. J Mater Eng Perform 28(7):4128–4142
29. Molina JM, Saravanan RA, Narciso J, Louis E (2004) Surface modification of 2014 aluminium alloy-Al_2O_3 particles composites by nickel electrochemical deposition. Mater Sci Eng A 383(2):299–306