Investigation of the Effect of Rice Husk Ash on the Fracture Toughness and Hardness of Al-Mn-Cr alloy

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Abstract: The used of agricultural wastes such as groundnut shells, coconut shell ash, rice husk ash (RHA), etc, as alternative strengthening materials to ceramics materials such as SiC, Al_2O_3 and SiO_2 for the fabrication of aluminum (Al) based composites has attracted so much interest in recent past. In this study, the effect of rice husk ash on the fracture toughness and hardness of Al-Mn-Cr alloy was investigated. The rice husk and scraps of Al used to produce the RHA and Al ingot respectively were acquired in Jos North LGA of Plateau state, Nigeria. Oxide composition of RHA contained high concentration of SiO_2, ZnO, CaO, Fe_2O_3 and P_2O_5 making it adequate for strengthening application. Also, the recycled scrap was found to be Al based alloy with 0.17%Mn and 0.02%Cr. The concentrations of the Mn and Cr in the recycled Al ingot were increased by adding 0.2, 0.4, 0.6, 0.8 and 1.0 weight percent of both Mn and Cr. The aluminium alloy composites (AMCs) were produced by adding RHA in weight percent of 0.2, 0.4, 0.6, 0.8 and 1% respectively. The AMCs were produced through stir casting. The fracture toughness and hardness of the AMCs were found to increase from 0.84 to 2.52MPa.m$^{1/2}$ and 48.67 to 82.67RHB with increased in the weight percent of Mn, Cr and RHA. This shows that the used of RHA in place of synthetic strengtheners such as SiC and Al_2O_3 cannot only reduced the cost of the AMCs produced using SiC and Al_2O_3 but the brittle nature of the AMCs. This produced composite can be used in automobile industries for the production parts such as connecting rods, brake disc, tar rods, piston, just to mention but a few.

Keywords: Aluminium scraps, Rice husk, Rice husk ash, manganese, chromium, fracture toughness, hardness, Al-Mn-Cr alloy, aluminum composite, -

1. Introduction

AMCs are metal matrix composites (MMCs) in which two or more materials are added to Al alloy as strengtheners (Asif et al, 2011, Surappa, 2003). AMCs are highly recommended for engineering structures such as aircraft body, ferries, missiles, satellites, heat exchangers, evaporators, radiators, connecting rod, crankshaft; etc due to their high thermal conductivity and corrosion resistance; and light weight. Light weight reduces fuel consumption and green house gas emission (Datau et al, 2020; Das, 2006).

AMCs produced using ceramics strengtheners like SiC and Al_2O_3 have good tensile properties, hardness, and wear resistance but low fracture toughness due to the brittle nature of these strengtheners (Surendran et al, 2014; Datau et al, 2020).

Other limitations of the AMCs produced using SiC and Al_2O_3 are that the composites are expensive and exhibit low strength properties at elevated temperature to the high cost of SiC, Al_2O_3 and Al alloy, and the low strength of Al alloy at elevated temperature (Silver et al, 2004).

Alloy scraps and RHA were used to reduce cost while alloying of alloy scraps with chromium and manganese elements was to improve the strength properties of the AMCs at elevated temperature (Ephraim et al, 2012; Joshi et al, 1995). RHA are produced from rice husk that exist in large quantity in most developing countries like Nigeria. About 120million tons of rice husk are produced every year. The presence of silica in addition to other oxides RHA has made it adequate for use as srengthener to produce AMCs (Sharma et al, 1984).

An alloy is a metal material that can be produced by adding two or more elements to the base metal. Over 90% of metals in use are alloys due to their superior properties to those of pure metals. Alloys are named from their base metal and other elements in order of their percentage concentration. Some examples of Al alloys are Al-Zn-Mg, Al-Zn-Mg-Cu, Al-Cu-Mn alloys, etc (Alaneme et al, 2016; Jokhio et al, 2007; Rana et al, 2012).

The alloying elements can increase the strength properties of alloys without significant increase in their weights. Some major alloying elements for aluminum are copper (Cu), magnesium (Mg), manganese (Mn), chromium (Cr) and zinc (Zn) (Richard et al, 2016; Rajneesh et al, 2013; Kaufman, 1999).

When fabricating a machine unit using different parts, it is difficult to eliminate completely the development of cracks. The presence of the cracks can cause premature failure of parts. Therefore, it is important to study the strength of part with induced cracks; and this strength characteristics fracture toughness (Michael et al, 2015; Gharebagh & Aghajani, 2011).

Rice husk (RH) is one of the most widely available agricultural wastes in Nigeria. RH are usually burned in a furnace to obtain RHA (Sangwan et al, 2013).

RHA is porous, light weight and has very high external surface area. RHA contain high concentration of silica (Wallheiner & Brian 2010; Kumar & Mohanta, 2012).

1.2 Fracture toughness

Fracture toughness is a measure of material resistance to crack extension. Measurement of fracture toughness is important for structural integrity assessment, damage tolerance design, fitness-for-service evaluation, and residual strength analysis. Also, the value of fracture toughness may serve as basis for material characterization, performance evaluation, and quality assurance for structures used in the following applications: nuclear pressure vessels and piping, petrochemical vessels and tanks, oil and gas pipelines, automotive, ship and aircrafts (Zhu & Joyce, 2017).

Linear elastic fracture mechanics (LEFM) was developed for the estimation of safety and life expectancy of structures with cracks. The stress intensity, K around the cracks is expressed as follows Zhu and Joyce, 2017):

$$K = \sigma\sqrt{\pi a} \text{ --------------------------(1)}$$

At fracture, the stress intensity factor reaches a critical value and it is expressed thus:

$$K_c = \sqrt{EG_c} = \sigma\sqrt{\pi a} \text{ --------------- (2)}$$

Where $G_c = \frac{\sigma^2 \pi a}{E}$ = energy required to cause fracture, σ = stress, α = crack length and E = elastic modulus, K_c = fracture toughness

Olamide and Oyewale (2012) produced and characterized RHA. They reported highest silica content and specific surface area at 700°C. Ephraim *et al* (2012) in their study on the grading analysis of RHA, reported particles distribution from coarse to fine particles. Hui et al (2012) studied the strain rate sensitivity of heat treated (T6) 7075 aluminum alloy. It was observed that the total elongation at fracture increased at temperature between 140^{0}C and 220°C because the increase in strain rate sensitivity prevents plastic strain from concentrating in a localize neck. Hossain et al (2017) investigated the impact, tensile, and compressive strength A356 aluminium alloy reinforced with rice husk ash in the weight 2%, 4% and 6% and produced through stir casting. It was observed that the composite with 6% exhibit maximum tensile, and compressive stress.

In this study, the fracture toughness of the AMCs produced using recycled Al alloy scraps and rice husk ash (RHA).

2.0 MATERIALS AND METHODS

2.1 MATERIALS/Equipment

The materials used for this study are Aluminum scraps, alloying elements (Manganese (Mn) and Chromium (Cr)), rice husk, rice husk ash, moulding sand, charcoal fired crucible furnace, Pyrometer, digital weighing scale, Oven, Stanton electric kiln, Electron gun, Desiccator, Pattern, Stirrer, Optical emission spectrometer, Energy Dispersive X-Ray fluorescence spectrometer, Rockwell hardness tester and Universal testing machine (Instron 3369)

2.2 Experimental method

2.2.1 Preparation of the rice husk ash

The rice husk was acquired from local millers at Odus in Jos North LGA of Plateau state. The husk was washed and then dried in the sun for four days. The husk was further dried by heating in an oven at 110^{o}C for 3hours. The dry husk was ball milled for 4hrs and sieved using set of sieves to obtain particles with average size of 80μm. The sieved husk was placed in a Stanton electric kiln of 500kg capacity (fig. 1) and heated at 800^{o}C for 5hours at the rate of 6.6^{o}C/min to obtain the Ash shown in fig. 2 below.

Fig.1 Stanton electric kiln

Fig.2 RHA

2.2.2 Analysis of the chemical composition of RHA

Energy Dispersive X-Ray Fluorescence was used to analyze the composition of RHA. The analysis was done according to the standard method (ASTM D6052 – 97

(2016)). The ash was sieved through a set of 200-250 mesh sieves, dried in an oven at 105°C for 1 hour and allowed to cool. Then 20g of the ash was weighed and mixed with a binder (cellulose flakes binder) in the ratio of 5:1. Pellets by compacting the ash in a pressure range of 137-206MPa using a pelletizing machine. The pellets were pre-heated in a desiccator for 2 hours. The computer attached to the ED-XRF machine (fig. 3) was turned on and the appropriate energy band levels were selected. Three specimens were used for the analysis. The result of the analysis is presented in table 1.

Fig. 3 Energy Dispersive –X-Ray Fluorescence

2.2.3 Preparation of aluminum alloy composites

The scraps of aluminum alloys were sourced from automobile workshop in Jos North LGA of Plateau state. The scraps were cleaned and washed with hot water to remove grease. The amount of the scraps to be melted in a charcoal fired crucible furnace was weighed using digital weighing scale and heated to 800°C. A thermo-couple was used to ascertain this temperature. At 750°C, the melt was poured into a prepared sand mould and allowed to solidify as shown in fig. 4 below. The casting was removed, cleaned and a specimen for chemical composition analysis of the recycled Al scraps was produced.

The amounts of chromium (Cr) and Manganese (Mn) to be added to Al scraps were determined using equation 3..

$$Amount\ of\ element(g) = \frac{(required\ \%\ conc\ of\ element - \%conc\ of element\ \ in\ scrap\ )*total\ charge\ (g)}{Purity\ \ of\ element\ \ (\%)}$$

3

From equation 3, the required % concentration of the elements referred the selected amount of Mn and Cr of 0.2%, 0.4%, 0.6%, 0.8% and 1.0% respectively. The % concentration of the elements in the scrap refers to the amounts of Mn and Cr present in the scraps (table 2). 99.8% was used as purity for Mn and Cr; and 300g was used as total charge mass. The computed amount of Mn and Cr are shown in table 2.

Similarly, the amounts of RHA to be added to the produced Al alloy were computed using equation 4.

Mass of RHA = %RHA x Mass of Al alloy -------------(4)

The concentrations of RHA in the alloy are 0.2%, 0.4%, 0.6%, 0.8% and 1%. Based on these concentrations and mass of Al alloy of 300g, the different amounts of RHA to be added to were determined as presented in table 2.

Table 1 Furnace charge calculation for Al-Mn-Cr-RHA Composites

Run	Composite	Al (g)	Mn (g)	Cr (g)	RHA(g)	**TC (g)**
1	Al-0.2%Mn-0.2%Cr-0.2%RHA	298.36	0.3	0.6	0.74	300.00
2	Al-0.4%Mn-0.4%Cr-0.4%RHA	296.59	0.7	1.2	1.51	”
3	Al-0.6%Mn-0.6%Cr-0.6%RHA	294.37	1.4	1.8	2.43	”
4	Al-0.8%Mn-0.8%Cr-0.8%RHA	292.42	2.0	2.4	3.18	”
5	Al-1.0%Mn-1.0%Cr-1.0%RHA	289.52	2.7	3.0	4.78	”

To produce the composites, the amounts of the components (Al scrap, Mn, Cr and RHA) for each composite formulation shown in table 2 above were weighed using a digital laboratory weighing scale. First, the weighed Al scrap was placed and heated to molten state at 800°C using a gas fired crucible furnace. A thermo-couple was used ascertain that the temperature of Al melt reached 800°C. The weighed amounts of Mn and Cr for the first composite were added to the melt and stirred using a steel stirrer for 2minutes. The weighed RHA was preheated to 300°C for 30 minutes in an Oven and added to the stirred Al melt. The mixture is then reheated to 800oC and stirred continuously for 5minutes. At 750°C the melt was poured into a prepared sand mould and allowed as shown in fig. 4. This procedure was repeated for other composite formulations shown in table 2 above.

Fig. 1 Digital weighing scale

Fig. 2 Cr and Mn metal elements

Fig. 3 Sand casting of composites

2.2.3.1 Analysis of the chemical composition of the Al alloy and Al alloy composite

Optical Emission Spectrometry (OES) shown in fig. 4 was used to analyze the amount of the elements present in the recycled Al alloy scraps in accordance with ASTM E415-99a. The specimen was ground to produce smooth surfaces. The Spectrometer was turned on and allowed to run for 3 hours. The specimen was placed in the electron gun, closed and spark was initiated to show the chemical composition in. The result of the analysis is presented in table 2.

Fig. 4 Optical emission spectrometer

2.2.4 Evaluation of hardness and fracture toughness of the composites

2.2.4.1 Hardness Test

Specimens for the hardness test were produced from the produced recycled Al alloy (control specimen) and the five different types of composites produced. The samples were first surfaced finished to achieve a flat surface. Then it was placed on a 4150AK Rockwell Hardness Tester with diamond indenter as shown in fig. 5. The prepared specimen or sample to be tested was mounted on the anvil of the hardness testing machine and the wheel of the machine was turned clockwise until the sample came in contact with the diamond cone indenter, the wheel was continually turn clockwise until the dial gauge indicator on the dial gauge/screen of the machine indicated zero. Then the start test button was pressed and the test was carried out by the machine, and the result was displayed on the dial gauge or screen. The test was repeated at three different on the surface of the specimen (fig.6) and the mean value determined.

Fig. 5 Rockwell hardness tester

Fig. 6 specimens for hardness test

2.7.2 Fracture toughness test

The specimens for the fracture toughness test were produced. A notch 0.2mm was machine at the centre as the pre-crack operation in accordance to ASTM E1304 standard test method fracture toughness of metallic material as shown in fig.7. Each specimen was fixed in a universal testing machine (Instron) 3369 shown in fig. 8 and load applied. The machine was set at a cross head speed of 1mm per minute, and the crack propagations was observed until the material fails. The results was been displayed on a computer software connected to the machine, this was done on sample 1 to sample 5 and the control and the result were gathered, while the fracture toughness was been analyzed from the raw data.

Fig. 7 Fracture toughness test sample

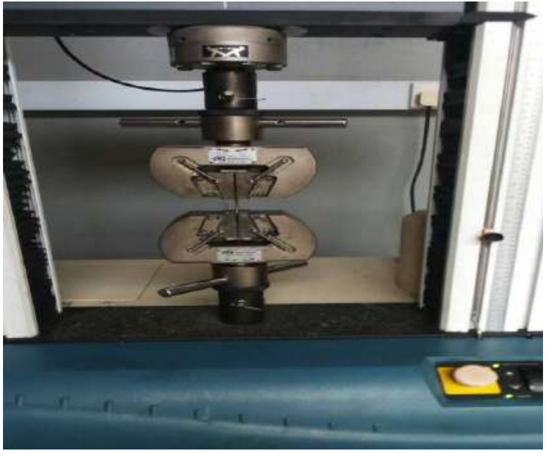

Fig.8 Universal testing machine (Instron 3369)

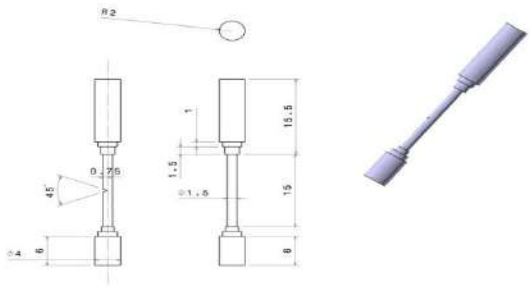

Fig. 9 Dimension of fracture toughness test specimens

Using the experimentally determined values of tensile stressed of the recycled Al scraps and the produced Al composites and notched value, the fracture toughness, K_c of the Al scraps and composites was evaluated using the following equation:

$$K_c = \sigma\sqrt{\pi a}$$

Where σ = ensile stresss at break (standard) (MPa), a = crack length notched at centre 0.2mm.

For instance, the fracture toughness of the control specimen (recycled Al scraps) was evaluated as follows:

$$\text{Control} \quad K_c = \sigma_1\sqrt{\pi a} = 33.60260 \times \pi \times 2 \times 10^{-4}$$

$$= 33.60260 \times 6.28319 \times 10^{-4}$$

$$=33.60260 \times 0.02507$$

$$=0.8423 MPa.m^{1/2.}$$

3. Results and Discussion

The results of the study that include the oxide composition of the RHA, chemical composition of the recycled Al scraps and the hardness and fracture toughness of the produced composites are presented in tables 1, 2 and 3.

3.1 Results

The following tables cover the results of this study

Table 1 Chemical composition (%) of rice husk ash (RHA)

SiO_2	P_2O_5	ZnO	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	NiO	CuO
79.30	6.33	5.21	3.15	0.24	0.05	0.34	3.66	0.01	0.07

Table 2 Chemical composition (%) of the recycled Al scraps

Al	Mg	Si	Mn	P	Cr	Mo	Ni	Cu	Ti	V	Se	Zn	Fe
91.86	0.35	6.82	0.17	0.01	0.022	0.01	0.02	0.18	0.19	0.02	0.02	0.32	0.21

Table 3 fracture toughness of the Recycled Al scraps and Al composites

Specimen	Tensile stress at break (standard) (MPa)	Fracture toughness ($MPa.m^{1/2}$)
Recycled Al scraps (control)	33.60	0.84
Al-0.2%Mn-0.2%Cr-0.2%RHA	82.94	2.08
Al-0.4%Mn-0.4%Cr-0.4%RHA	86.43	2.17
Al-0.6%Mn-0.6%Cr-0.6%RHA	88.67	2.22
Al-0.8%Mn-0.8%Cr-0.8%RHA	94.08	2.36
Al-1.0%Mn-1.0%Cr-1.0%RHA	100.68	2.52

Table 4 Hardness of the recycled Al scraps & Al composites

Specimen	Hard (HRB)
Recycled Al scraps (control)	48.67
Al-0.2%Mn-0.2%Cr-0.2%RHA	57.67
Al-0.4%Mn-0.4%Cr-0.4%RHA	67.33
Al-0.6%Mn-0.6%Cr-0.6%RHA	77.33
Al-0.8%Mn-0.8%Cr-0.8%RHA	80.67
Al-1.0%Mn-1.0%Cr-1.0%RHA	82.67

3.2 Discussion of results

3.2.1 Chemical composition of RHA

The results of analysis showed that the chemical composition of rice husk ash varies for rice husks from different locations. It can be inferred that geographical location, climate conditions and type of fertilizer applied to rice farms during cultivation have effect on the oxide composition of RHA (Govindarao, 1980). The RHA used for this study has high concentration of SiO_2, P_2O_5, ZnO, CaO, and Fe_2O_3 as shown in table 1 and these oxides made it adequate for use as strengthener in producing Al based composites.

3.2.2 Chemical composition of the recycled Al scraps

The elemental analysis carried out on the aluminum recycled from the scraps showed the scraps to Al based alloy with high concentration of Si. However the following elements were found in the scraps but at low concentrations: Mg, Zn, Cu, Mn, Cr, Fe and Ti. The concentration of Al is 91.86% as shown in table 2. The scraps can be used to produce Al alloys that are cheaper than the primary Al alloys for structural applications by upgrading the concentrations of some of the elements in it to improve their properties.

3.2.3 Fracture toughness of the produced composites

The evaluated fracture toughness of the recycled Al scraps (control specimen) and the produced composites presented in table 3 showed increase in the fracture toughness from $0.84MPa.m^{1/2}$ (control specimen) to $2.52MPa.m^{1/2}$ (composites with 1%Mn, 1%Cr & 1%RHA); and the corresponding maximum tensile stresses are 58.33MPa (control specimen) and 102.28MPa (composite). The fracture toughness increased with increase in RHA, chromium and manganese additions to the recycled Al scraps. The stress versus strain plot obtained during the fracture toughness test is presented in fig. 4 below.

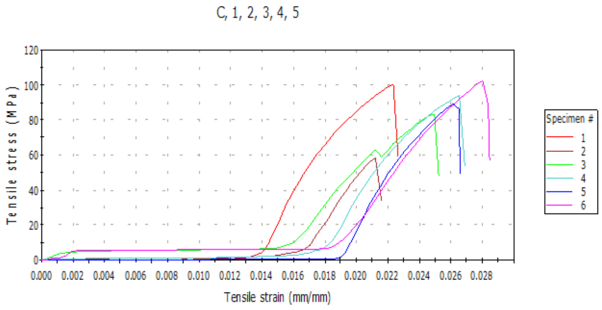

Fig. 11 Tensile stress versus tensile strain

From fig. 11, it is observed that the tensile stress increased as the applied load was increased. As the straining increases, the tensile stress increased greatly until it attend maximum. Fracture occurred at maximum stress making the sudden the stress to drop sharply. The control specimen undergoes more straining than the composites and such it has less tensile stress than those of the composites.

3.2.4 Hardness of the recycled Al scraps and the composites

From fig. 12 below it is observed that the hardness of the composites increased with increased in the RHA concentration. The increase in hardness is more at low concentration of RHA additions (0.2% to 0.6%) than at high concentrations of RHA (0.8% and 1%). The hardness increased from 48.67(HRB) (control specimen) to 82.67(HRB) (composite with 1% Mn, Cr and RHA)

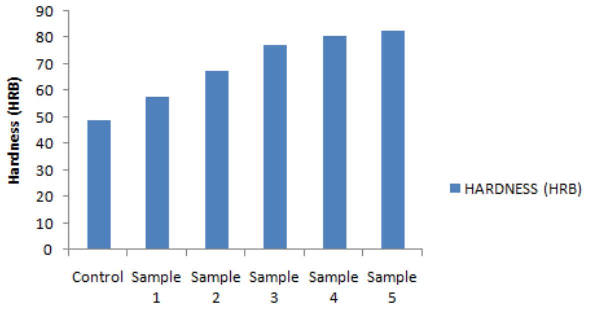

Fig. 12Hardness of recycled Al scraps & Al composites

4. Conclusion

From the study, the following conclusions were made:

i. The analysis of oxides composition in the RHA showed high concentrations of SiO_2, P_2O_5, ZnO, CaO and Fe_2O_3 which made it adequate for used as a strengthening agent for the fabrication of the composite. Therefore, using the RHA due to the high concentration of SiO_2 of 79.3% as alternative to synthetic SiO_2 to produce Al based composites not only economical but has less environmental effect.

ii. The elemental composition showed that the recycled scraps is Al based alloy with high concentration of Si (6.82%) compare to other elements like Mg (0.35%), Zn (0.32%), Mn (0.17%), Cr (0.02%), Cu (0.18%, Fe (0.21%), Ti (0.19%), etc. Therefore, upgrading the concentrations of the elements in the alloy can lead to improvement in the properties of alloy for structural applications.

iii. The used of RHA can reduce the cost of the Al composite as compared to those produced using synthetic strengtheners like SiC, Al_2O_3 and SiO_2

iv. From the study, it is observed that fracture toughness and hardness increased with increase in Cr, Mn and RHA additions.

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