Physico-Mechanical Characterization of Iron chips-Kaolinite Clay Particles Reinforced Aluminium Metal Matrix Hybrid Composite

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ABSTRACT

A hybrid of iron chips and kaolinite clay fillers reinforced aluminium metal matrix composite material was developed. The composites samples were produced using stir casting method. Results of the characterization tests showed that both the iron chips and kaolinite clay particulate fillers increased the tensile and flexural strength while only kaolinite clay is effective in increasing the impact energy. The optimum formulation of the properties was determined at 13.97%, 18.15% and 67.88% of kaolinite clay, iron chips particles and aluminium metal matrix respectively. Overall, the maximum tensile strength and flexural strength (sample 5) were improved by 54% and 78% respectively as compared to the control sample.

Keywords: Kankara clay; iron chips; aluminium metal matrix; mixture design; hybrid composite.

1. INTRODUCTION

Research in composite materials is continuously leading to new development in hybrid metal matrix composite with enormous applications in marine, automotive, aerospace and medical fields [1]. Some of the recent works on development and characterization of metal matrix composites have been summarized thus. Alaneme et al. [2] characterized the mechanical behavior of rice husk ash-alumina reinforced Al-Mg-Si alloy metal matrix composite and found that the specific strength, percentage elongation and fracture toughness were higher as compared with the only alumina reinforced composite. Rajmohan et al. [3] investigated the synthesis and characterization of SiC and nanocopper oxide (CuO) particles hybrid aluminium metal matrix composite and found that increase in percentage weight of the nanoparticles improved the mechanical properties and density. Baskaran et al. [4] characterized aluminium metal matrix composite reinforced with TiC and TiO_2 and discovered that the hardness, wear rate and density increased with addition of TiC and TiO_2 content. Sarada et al. [5] developed LM 25+ activated carbon and mica reinforced aluminium metal matrix composite and found that addition of the hybrid reinforcements increased the hardness and the wear resistance of the composite as compared with the LM 25+ activated carbon and LM 25+ mica composites. Dwivedi et al. [6] synthesized and characterized eggshell reinforced aluminium metal matrix green composite and found that the tensile strength, hardness and fatigue strength were improved by 32.9, 31.66 and 19.55% respectively with addition of 5 wt% carbonized eggshell particles. Chauhan et al. [7] characterized the mechanical properties of alumina and fly-ash hybrid reinforced aluminium (Al6061) metal matrix produced using stir casting and found that the tensile strength and hardness were improved. Kumar and Birru [8] studied the microstructure and the mechanical properties of bamboo leaf ash (BLA) reinforced aluminium metal matrix composite and found improvement in the tensile strength with homogeneous distribution of the BLA particles in the composite.

Suitable design of experiment is vital to develop a composite material with adequate pre-experimental formulation and optimized output results [9]. Many researchers have employed mixture, RSM and other types of experimental design to design, analyse/evaluate, model and optimize their experiments. Dan-asabe et al. [10] modelled and optimized the properties of a periwinkle-palm kernel and phenolic resin composite brake pad using RSM. Nasouri and Shoushtari [11] designed, modelled and manufactured a lightweight carbon nanotubes/polymer composite nanofiber for electromagnetic interference shielding application using RSM.

This research work involved constituent materials mixture design, characterization, analysis and optimization of kaolinite clay-iron particles reinforced aluminium metal matrix hybrid composite.

2. EXPERIMENT

2.1 Materials

The materials used are scrap annealed [12] aluminum AA1050A scrap (7.0kg), kaolinite (Kankara clay, 2.0kg) and iron chips waste (3.0kg). The equipment used in this experiment are stir casting machine furnace, graphite crucible, impact testing machine (Charpy Hounsfield), universal flexural testing machine, tensile testing machine (Hounsfield tensometer) and structural electron microscopy (SEM) machine.

2.2 Experimental Design

The design input factors used are in weight percentage comprising of iron chips particles, Kankara clay, and aluminium matrix in accordance with a similar mixture design as employed by Fatoni [13] and Dan-asabe et al. [14]. A constrained bound ranges for the constituents (factors) was employed using Design Expert 11.0 [15, 16] is given as follows:

$$0 \leq x_1 \leq 30\% \tag{1}$$
$$0 \leq x_2 \leq 25\% \tag{2}$$
$$65\% \leq x_3 \leq 100\% \tag{3}$$

where x_1, x_2 and x_3 represents percentage weights of iron chips particles, kaolinite (Kankara) clay and aluminium matrix respectively. Seven design points (Table 1) were considered comprising of 6 (six) triplet blends and one pure blend (control sample). The actual experiment was replicated thrice (Fig. 1a) and the averages for tensile strength, flexural strength, impact energy and density were calculated as shown in Table 2. The fraction of design (FDS) curve at 82% (Fig. 1b) gives a standard deviation error of 1.578 close to an average of 1.404 (a flatter curve), indicating a good design with less variation of error covering a greater portion (81%) of the design space. This is expected of a good design curves with high precision in model prediction as reported by Fatoni et al. [13].

Table 1. Design points of the hybrid mixture design

Design points/ samples	Actual Composition (%)		
	x_1	x_2	x_3
1	0	0	100
2	15	5	80
3	5	10	85
4	10	15	75
5	15	20	65
6	5	25	70
7	30	5	65

Table 2. Characterization results

Design Points/ samples	Tensile strength (MPa)	Flexural strength (MPa)	Impact energy (J)	Density (g/cm^3)
1	62	95.35	8.9	2.5
2	53	77.08	6.4	2.4
3	45	86.26	6.7	2.6
4	68	92.82	6.9	2.6
5	83	147.77	9.8	2.2

6	50	96.65	5.9	2.6
7	44	102.43	8.1	2.3

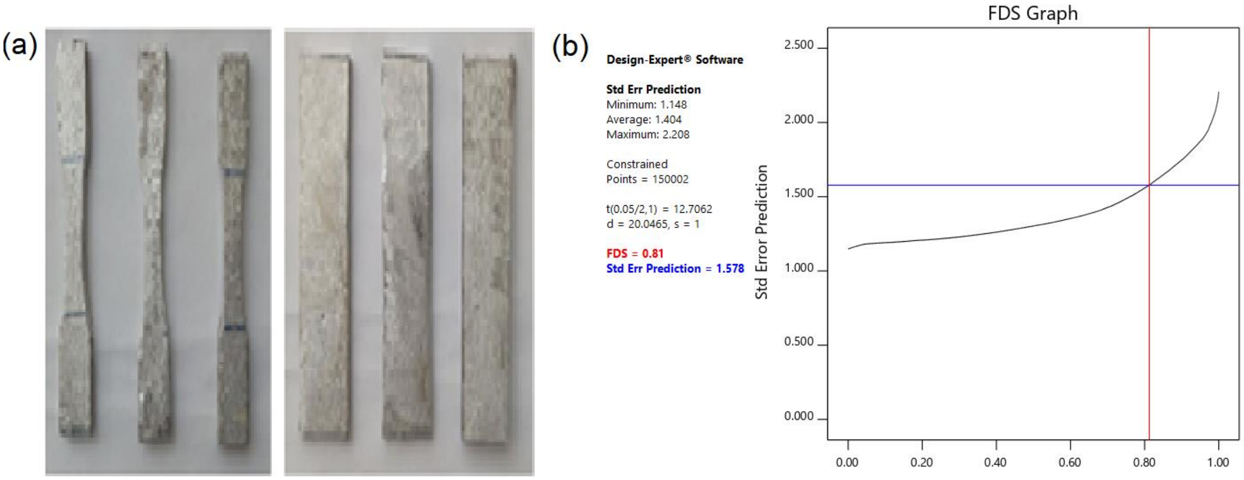

Fig. 1. (a) Tensile and flexural test composite samples; (b) Fraction of the design space against standard error prediction

2.3 Materials preparation and composite fabrication

The aluminum and iron chip scraps were purified to remove impurities by carefully washing the scraps and rinsing. The aluminum and iron chips were dried and the iron chips was crushed into smaller sizes using stone crusher and further grinded into fine particles. The fine iron chips and the kaolinite clay were sieved through a 150μm sieve. The hybrid composite material was produced using stir casting method. First the iron particles and kaolinite (Kankara clay) particles were separately preheated to a temperature close to that of the melting of the matrix (aluminium) while below their melting points. Aluminium alloy AA6061 ingot was initially preheated for 3–4 hrs at 500°C and then subsequently heated to melting at 820°C in a graphite crucible in the furnace. The preheated fillers were thoroughly mixed [17] and added into the crucible. The corresponding mixture was stirred to uniformly disperse the reinforcing fillers in the aluminium alloy matrix. The speed of the stirring was done at 400rpm for 10 minutes. The temperature of the furnace was controlled at 820 ± 10 °C in final mixing process.

3. CHARACTERIZATION

The characterization involved determining the density, tensile strength, flexural strength, impact energy and SEM micrograph. The hybrid composite density was determined by measuring its respective mass using a digital weighing balance and volume by measuring its length, breath and width [18]. Thus the density of each sample was determined using equation 4:

$$\rho = \frac{m}{v} \quad (\text{g/cm}^3) \qquad (4)$$

The tensile strength was determined using an Electronic Tensometer ER–3 according to ASTM B557M [19] standard. Sample specimen dimensions of $60\times10\times5$ mm^3 with dumb bell shape were produced for the test. The dumb bell part was clamped to jaws of the Tensometer leaving out a gauge length of 40 mm and the extension was produced within the gauge span of the specimen. The tensile strength was calculated using equation 5:

$$\sigma = \frac{P}{A} \quad (\text{MPa}) \qquad (5)$$

where P = maximum force (N) and A = cross-sectional area of gauge length (mm^2)

The flexural strength was carried out according to ASTM E290 [20] using Universal (digital) testing machine (EnerPac P-391). Samples of dimensions 100×10×5 mm^3 were prepared for the test. The test sample was placed between two rollers and a force (hydraulic handle) was applied until the sample ruptured. The flexural strength was calculated using equation 6:

$$F = \frac{3Pl}{2bd^2} \text{ (MPa)} \qquad (6)$$

where $P =$ maximum deflection force (N), l = length of specimen (mm), d = maximum deflection (m) and b = width of specimen (mm).

The impact energy was determined using the Avery Denison Charpy Impact Test Machine (S-3203) on the notched samples. The sample specimen of dimensions 55×10×5 mm^3 and 2 mm deep notch with radius of 0.25 mm at an angle of 45º were produced according to ASTM F2231 [21]. The test sample was placed in the slot of one of the two pendulums and firmly held with the aid of a spring loaded pin. The other pendulum (the stopper) causes the impact when the two (pendulums) are swung in action.

The microscopy of the hybrid composite was determined using a JOEL field emission electron microscope JSM- 7600F. Specimen of dimension 20×20×5 mm^3 were produced for the tests according ASTM E175-82 [22].

4. RESULTS AND DISCUSSION

4.1 Physical and mechanical properties (Density, SEM, tensile, flexural strength and impact energy)

The three-constituent contour plot of the tensile strength is shown in Fig. 2a. The plot shows the variation of the tensile strength increasing (blue to green to yellow to red colours) as the percentage of the respective iron and kaolinite clay content increases with decreasing content of the aluminium matrix. The higher tensile strength contour (green to yellow to red colour) is more dominant at edge (highest content of 30%) of the iron content than at the edge of the kaolinite clay, implying significant effect of the iron content in increasing the tensile strength. The contour plot of the flexural strength (Fig. 2b) showed similar trend as that of the tensile strength with increasing iron content having a more substantial effect in increasing the flexural strength. The result supports the fact that metals (iron, aluminium, copper etc) are known to have (influence) ductility i.e. a characteristic nature of higher (improved) flexural or tensile strength.

The contour plot of the impact energy (Fig. 3a) showed increasing (blue to green to yellow to red colours) as the percentage of the kaolinite clay content increases with decreasing content of the aluminium matrix. It also showed a partial increase and then decrease of the impact energy as the percentage of iron content is increased.

Contour plot of the density shown in Fig. 3b showed that increase in the percentage of iron content increased the density while increase in percentage of kaolinite clay decreased the density. This supports the fact that iron is denser than kaolinite (Kankara) clay.

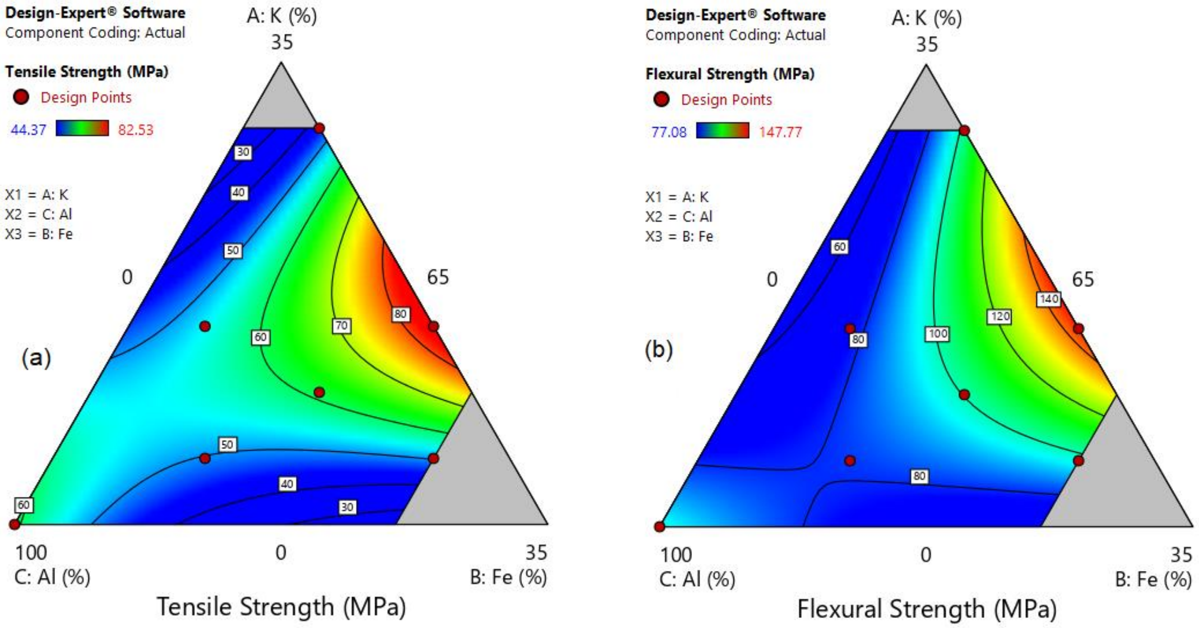

Fig. 2. Contour plots of the: (a) Tensile strength; (b) Flexural strength

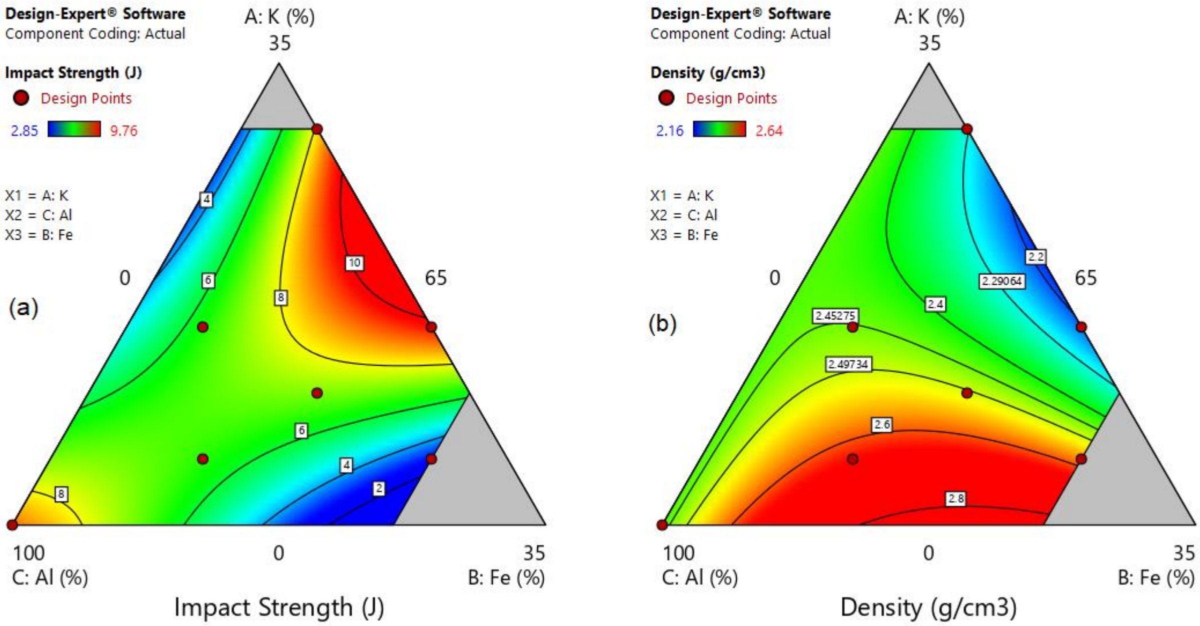

Fig. 3. Contour plots of the: (c) Impact energy; (d) Density

4.2 Effects of Two (2) Factor Constituents

The effects of two constituents (iron particle reinforced aluminium matrix while keeping the kaolinite clay constant or kaolinite clay reinforced aluminium matrix while keeping iron content constant) of the hybrid composite was analyzed. Figs. 4a and 4b respectively showed that the tensile and flexural strengths increased with increase in the percentage compositions of both the iron and Kankara clay contents. The trends in the Figures also showed that iron content (higher dashed curve) is more effective in increasing the tensile and flexural properties. The result was in agreement by Rajmahan et al. [4] who found that addition of metallic particles (nanocopper oxide) increased the tensile strength of hybrid aluminium matrix composites reinforced with nanocopper oxide particles and microsilicon carbide particles. The result also agreed with Chauhan et al. [8] that addition of hybrid fillers of alumina and fly-ash increases the tensile strength of aluminium matrix composite reinforced with alumina and fly-ash.

Fig. 5a showed the impact energy increases with increasing kaolinite clay while it increases and decreases with iron contents. The result indicates that iron content does not have effect on the impact energy. Fig. 5b showed the density of the hybrid composite while maintaining a constant aluminium matrix content. The trend depicted a decreasing curve as the percentage content of kaolinite clay is increased while simultaneously decreasing the iron content, thus implying that iron or its alloy i.e. steel [23] having room temperature density of 7.86g/cm^3 is denser than kaolinite (Kankara) clay with density of 1.8g/cm^3 [24] in increasing the overall composite density. Kankara clay is less dense than iron and aluminium and thus increase in its percentage (with simultaneous decrease in iron content) decreases the overall density.

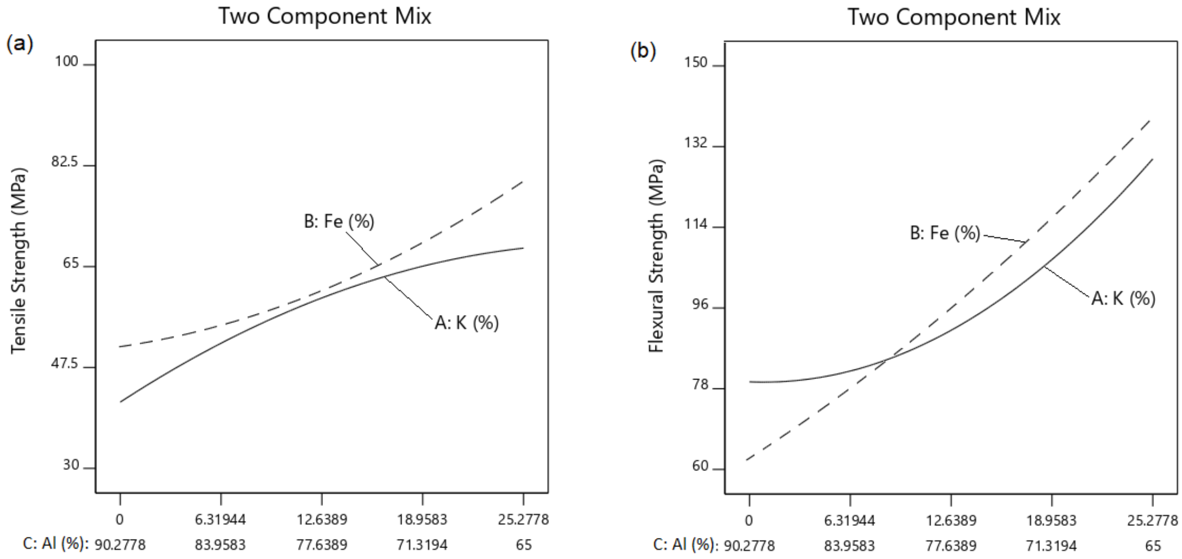

Fig 4. Effect of each filler and aluminium matrix with; (a) Tensile strength (b) Flexural strength

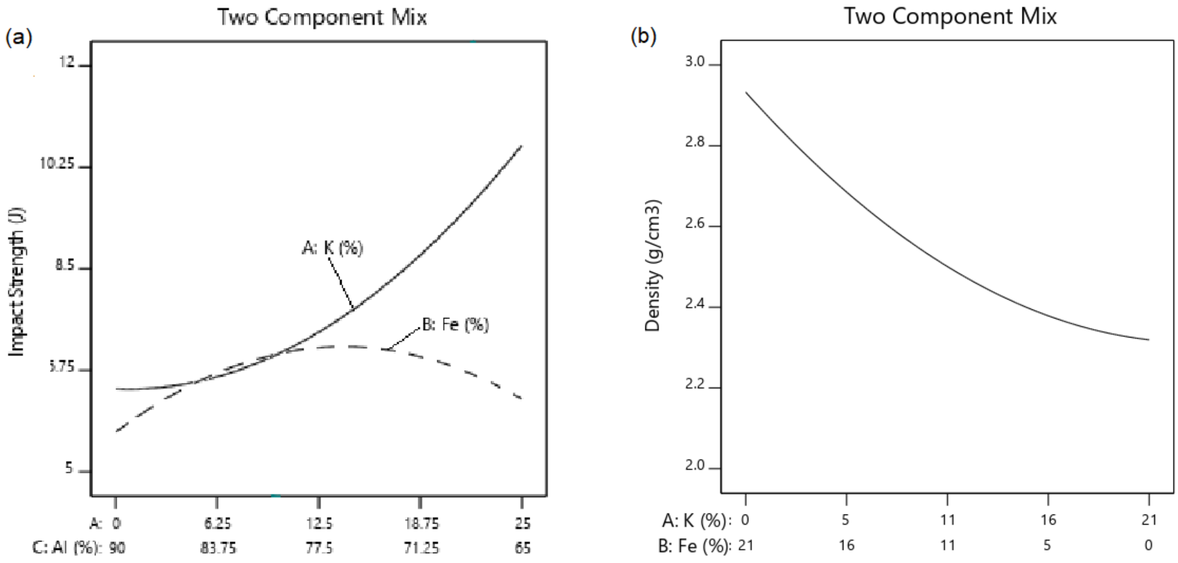

Fig 5. Effect of each filler and aluminium matrix with; (a) Impact energy; (b) Density

4.3 Optimisation

Optimization was carried out in terms of desirability (optimum constituent formulation). The optimization objective is to maximize the tensile and flexural strength. The impact energy was only kept within its range values since it showed a decreasing trend. However, density maximization or minimization may be insignifant as its (range) values are low (approximately equal to one). Thus desirability formulation (highest point in the curve of Fig. 6a) is 98.2% corresponding to optimum formulation with 18.61, 16.48 and 67.88% of iron, Kankara clay and aluminium matrix respectively. This also corresponds to a tensile strength of 85MPa, flexural strength of 146MPa, impact energy of 10.9J and density of 2.2g/cm^3.

4.4 SEM Micrograph

The SEM micrograph at 1000 magnification and 268μm of the control and the optimum sample (maximized sample) are depicted in Figs. 6b and 6c respectively. The control shows the glossy aluminium matrix with minor black spots defects of fracture dents. The micrograph of the maximized sample shows fair distribution of the iron particles (small black spots) and sparsely visible spots of the Kankara clay. The Kankara clay could have been dissolved in the aluminium matrix and only very limited spots that is insoluble (precipitated) were noticeable. The part solubility of the Kankara clay in the aluminium matrix could also have caused the diminishing of the glossy aluminium surface as compared with the control sample.

4.5 Application of the composite

The composite can find use as a potential substitute in for aluminium alloy roofing sheets. The composite with best property (Sample 5) with 83MPa tensile strength is comparatively better than Obam and Taku [25] and industrial aluminium brands [26] with maximum of 52MPa and 77MPa respectively. Comparative composite density (Sample 5) of 2.2gcm^3 is less dense as compared with Obam and Taku (2015) having 2.6gcm^3.

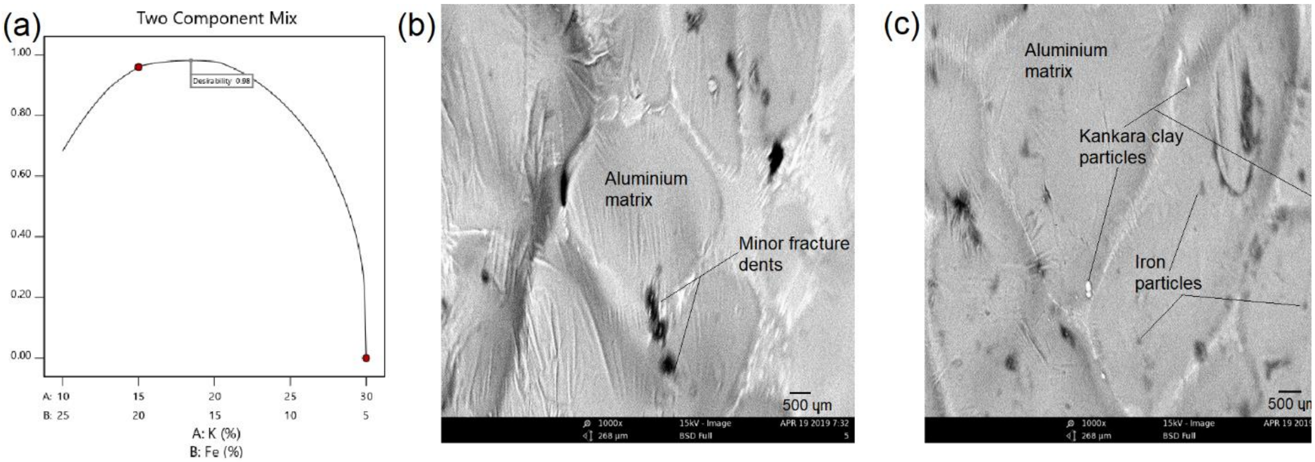

Fig. 6. (a) Desirability plot of the hybrid composite; (b) SEM micrograph of sample 1 (control sample); (c) SEM micrograph of sample 5

5. CONCLUSION

In conclusion, results from the characterization and analysis of the hybrid composite showed that both iron and kaolinite (Kankara) clay contents are effective in increasing the tensile and flexural strength with iron content being more significant in this respect. The result also showed that only Kankara clay content is effective in increasing the impact energy. Kankara clay content decreases the density of the hybrid composite while iron content increases it due to its relatively higher density. Optimization result formulation of 13.97, 18.15 and 67.88% of iron, Kankara clay and aluminium matrix respectively showed close values to sample 5 of maximum 15, 20 and 65% respectively.

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