Mechanical Behavior of A356/Albite Composite Material

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Abstract: The present investigation aims to study the effect of Albite ceramic on the microstructure and mechanical characterizations of A356 aluminum/composite containing reinforcement of 3 percent by weight and (2-20) µm particles' size. The composite was fabricated using 'stir-casting' method in which the particles were added to molten alloy at semi-solid state during stirring process at rotating speed 700 r.p.m. Metallographic investigation of the fabricated samples as well as the mechanical properties; (tensile, compression, impact and hardness.) were studied. The results of study revealed that; adding Albite to A356 alloy has significantly increased the tensile strength as well as elongation percent with 18% and 25% respectively. Also higher compression yield strength and relative elastic strain with 17 % and 37.5% in sequence were achieved than that of the unreinforced alloy, while marginal increase in compressive strength in plastic zones has been obtained. The addition of Albite ceramic to the A356 alloy has improved the fracture toughness by about 12 %, a slight increase in hardness was observed as a result of the inserting Albite dispersions into the matrix alloy, on the macrohardness scale.

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Key words: Aluminum silicon A356, Albite, MMCs, microstructure, and mechanical properties.

1. Introduction

Metal-matrix composites (MMCs) have been attracting growing interest. MMCs' attributes include alterations in mechanical behavior (e.g., tensile; compressive, creep, notch resistance, and tribological properties) and physical properties (e.g., intermediate density, thermal expansion, and thermal diffusivity) by the filler phase [1]. Engineering interests in aluminum-based metal matrix composites (MMCs) has increased [2]. Among Aluminum alloys, Aluminum-Silicon (Al-Si) alloys are most versatile materials, comprising 85% to 90% of the total aluminum cast parts produced for the automotive industry, depending on the Si concentration in weight percent (wt.%) in the AI-Si alloy systems[3]. Particulate reinforced MMC's have recently found special interest because of their high specific strength and specific stiffness at room or elevated temperatures. Interest in particulate reinforced aluminum MMCs is mainly due to easy availability of particles and economic processing technique adopted for producing them [4]. A great portion of the research efforts is focused on producing the MMCs by solidification processing, which is likely to be more economical and relatively simple in comparison with the competing solid processing [2]. Studying the characterization and mechanical properties of unreinforced A356 alloy in different conditions as well as (A 356-3%Albite) MMC is the purpose of the present search. There is a leakage of information about MMCs reinforced with Albite ceramic. Albite is a common feldspar ceramic, a mineral aluminosilicate ($NaAlSi_3O_8$) that occurs most widely in acid igneous rocks such as granites [4,5]. It's basically consisting of silicates; it is abundantly available in the Earth's crust. Albite ranges from white to dark grey in color and is extremely wear resistant, having a Moh hardness of about 6.5, almost rivaling that of SiC but exceeding that of alumina. It does not react with the matrix material in this case, even at elevated temperatures, and has a low coefficient of thermal expansion of 2.3 x 10^{-6} C^{-1}. Also it's low thermal conductivity (2.8 $W.m^{-1}.C^{-1}$) and specific gravity (2.6 g/cm^3) which is much lower than those of SiC (3.1 g/cm^3) and alumina (4.0 g/cm^3) [4,6]. These properties make Albite a candidate reinforcement material in MMCs. In the present investigation, vortex method and forming in semi-solid state (SSM) route was adopted to produce A356 alloy as well as composite material in die casting, several advantages of semi-solid forming process are proved, the most important of these, in the view of most technologists today, is the non-turbulent filling of the die, which results from the high and controllable viscosity of the semi-solid material. This smooth mold filling eliminates the air entrapment encountered in the conventional die-casting process and results in parts of high integrity, with superior mechanical properties [7, 8].

2-Experimental work

2-1-Materials

A356 alloy was used to prepare three different materials via rheo-casting technique; as cast and cast stirred A356 alloy and (A356-3%Albite) MMC material. Chemical composition of both matrix and reinforcement (Albite) materials are listed in table (1) by weight fraction 3 percent. Particle size of Albite powder is ranges from 2- 20 µm.

Table (1) Chemical compositions

A356	Element	Si	Mg	Fe	Sn	Al		
	Composition%	7.65	0.42	0.143	0.013	Bal		
Albite	Element	SiO2	Al2O3	Na2O	CaO	Fe2O3	TiO2	K2O
($NaAlSi_3O_8$)	Composition%	66.63	18.74	10.73	1.25	0.45	0.33	0.33

2-2-Equipment

A stir casting setup consisting of resistance furnace with a mechanical stirrer unit and heat control system was specially designed and constructed for materials casting (Figure 1). Also 40 ϕ ×180 mm cylindrical stainless steel mold is prepared to permit escaping gases from molten through a narrow holed base during pouring process, where as die casting and permanent mold methods have been used extensively in manufacturing light-weight castings but porosity existence in such castings is a quality limitation [8].

2-3-Materials preparation

Referred to the SSM route, materials preparation was done in mushy zone of molten metal. **Robert *et al*.**[9] show the solidification range of A356 alloy lies between the solidus and liquidus temperature of 578 and 618 ºC with accuracy of ± 2 ºC . According to **Shueiwan** [10]; the material can have a good fluidity when the solid fraction is as high as 60%. Aluminum in the form of rectangular ingots was cut into pieces to accommodate a SiC crucible. The metal alloy heated up to melting temperature (630 ºC). The molten was degassed in fully liquid state with (Na-Cl and KF) mixture then skimmed, followed with degassing by pure argon for 40 seconds. The melt temperature was lowered down to semi-solid state (590-600 ºC), then poured soon into preheated mold at 150 ºC to prepare as cast alloy. Anther casting heat has been stirred using stainless steel impeller with diameter equal 13 mm and 4 blades for 90 sec with rotation speed ranges from 600 to 800 r.p.m. before pouring to prepare stirred unreinforced alloy. Also preheating Albite particles was done at 500 ºC for 50 min, but being Albite ceramic has extremely poor wettability, it was added at slurry with 580 ºC where melt had higher viscosity and particles entrapping into molten was easier. Molten has been solidified at the end of consolidation process. So solidified molten temperature was raised till slurry reached (590 to 600 ºC), thence it was poured soon. Raising molten temperature after consolidation process has not permit powder floating because it still made slurry in semi solid state. The structure has been investigated by micrograph.

Figure 1: Setup of stir casting.

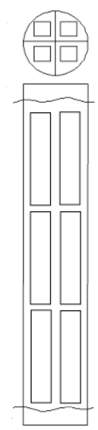


Figure 2: Samples cutting from ingot

2.4 Sampling

Cast ingots were cut as shown in figure (2) to prepare standard specimens for mechanical characterization.

2.5 Microstructure Characterization

2.5.1 Optical Microscopy

Samples were prepared following the standard metallographic procedure for carrying out metallurgical studies using Keller's reagent (2ml HF, 3ml HCL, 5 ml HNO_3, 190 ml H_20) for 30 seconds. The microstructure was conducted on the surface of polished samples using Olympus-12 optical microscope.

2.5.2 Scanning Electron Microscope (SEM)

The surface topography and fracture characteristics were examined by (Joel JSM 5410) using (Oxford-IMCA) for scanning electron micrographs.

2.6 Mechanical Characterization

2.6.1 Tensile test

Tensile specimens of 3.5 mm diameter and 19.5 mm gauge length were prepared to subject to tensile test at applied load 5 KN on Monsanto extensometer tensile testing machine with capacity of 20 KN.

2.6.2 Compression test

Samples with 10 mm diameter and (L/d) have unity ratio were prepared to apply compression test on Hung Ta Instrument with 50 ton capacity.

2.6.3 Hardness test

It was carried out at HV-50A, (measuring range: 5˷2900 HV), 30 sec applied time and 1 kgf were applied onto polished surface of samples.

2.6.4 Impact test

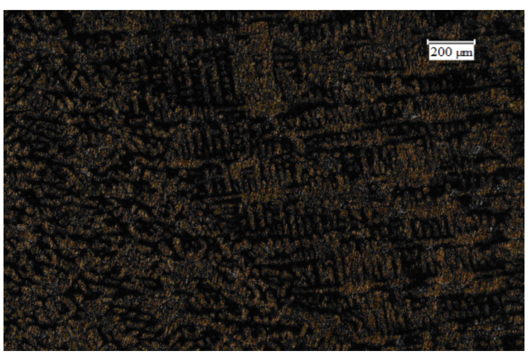
Impact test was conducted on un-notched specimen with dimensions 10×10×55 *mm*, the test was performed using RKP 450 Pendulum impact testing machine with capacity of 350 Joule and testing temperature 20.7 ºC.

3. Results and Discussion

3.1 Metallography

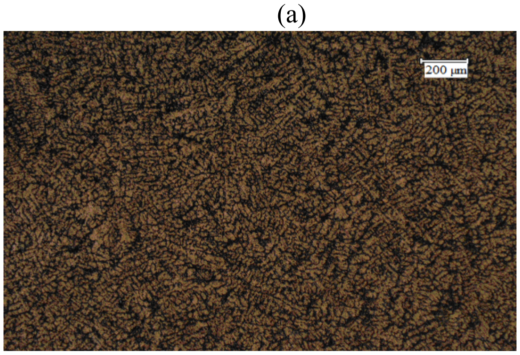
3.1.1 Optical Microstructure

Optical images of samples are shown in figure (3). Figure (3-a) shows the coarse dendritic structure of the commercial A356 alloy (as received). This is due to the high casting temperature which creates a wide solidification range. The received alloy is used to produce three test types of materials; as cast alloy with and without stirring and (A356- 3% Albite) MMC material. It is noted that the dendritic structure has been refined when the received alloy was treated with casting at temperature (590-600 ºC), in which solidification range is reduced (Figure 3-b). The dendritic structure has been minimized with the mechanical stirring during casting the A356 alloy as well as in the MMC (Figures 3 c &d). However the casting at SSM produces a narrow solidification range [7] and thus super cooling effect can be avoided [11]. These results are confirmed with Shueiwan and Shyh-Ming [10]. Also figure (3-d) shows that equiaxed and finer grains in (A356-Albite) MMC than that appear in unreinforced alloy (Figure 3-c). Basically, grain refining in the (A356-Albite) MMC was caused by double refining mechanisms, the first; present fine particles (2-20 μ m) in the molten which acts as nuclei and hence accelerate the solidification process and the second; the chemical composition of Albite ceramic ($NaAlSi_3O_8$) that contains Na element enhanced refining effect.

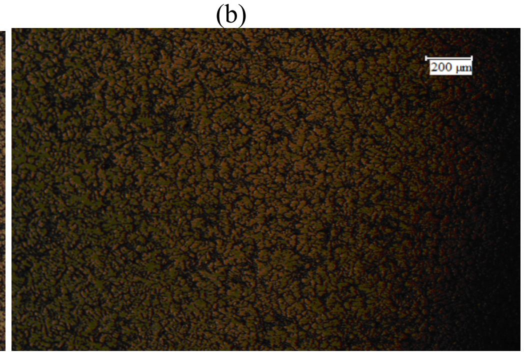


(a)

(b)



(c)



(d)

Figure 3: Microstructure of (a) As received A356 alloy, (b) As cast A356 alloy, (c) Cast A356 alloy with mechanical stirring, and (d) (A356-3%Albite) MMC respectively.

3.1.2 SEM and EDAX Analysis

The surface topography examination of (A356-3%Albite) MMC by SEM is shown in figure (4). A uniform distribution of 3% Albite particles inside the matrix alloy without agglomeration is clear from figure (4.a). Also higher magnification (detail A) is observed as in figure (4.b), the Albite particle size is measured and analyzed by EDAX. The analysis of ceramic is shown in figure (4.c), chemical stability of Albite particle at elevated temperature during casting is indicated from EDAX analysis.

3.2 Tensile properties

The results of tensile test are shown in figure (5), each result is an average of ten readings of both ultimate tensile strength and ductility. Figure (5) indicates that the average UTS changed from 102.5 MPa for the commercial received A356 alloy to 160 MPa for as cast alloy in SSM, to 170 MPa with applying mechanical stirring into cast alloy to 200 MPa with 3% Albite addition. On the other hand the elongation % changed from 2 % for the received A356 alloy to 6% for both as cast and stirred alloy, and 7.5% with Albite addition. Results in figure (3) are evident that adding the fine Albite-particles in low weight fraction caused an increase in both tensile strength and elongation % of the reinforced A356 alloy. Also pictorial photo of (A356-3%Albite) MMC's broken sample is shown in figure (6).

It is noted that the casting conditions affects the alloy structure and hence yields large change in both UTS and ductility. Similar data has been obtained before by Shueiwan [10] who explained how the alloy structure enhances the mechanical properties. Khomamizadeh and Ghasemi[12] discuss the improvement of mechanical properties referring to the grain refining caused by high solidification rate. The grain refining mechanism of (A 356-3%Albite) MMC is explained in microstructure paragraph. However, the improvement of tensile properties of (A356-3%Albite) MMC is due to grain refining effect, beside stress transformation from the weak matrix to the stiffer particles phase.

Similar tensile strength improvement was obtained by **Ramesh** [4] who incorporated Albite with (90 to150 μ m) particle size with 6061 Al alloy but it was on the account of ductility. Perhaps, using coarse particles of Albite in his study reduced matrix alloy's ductility.

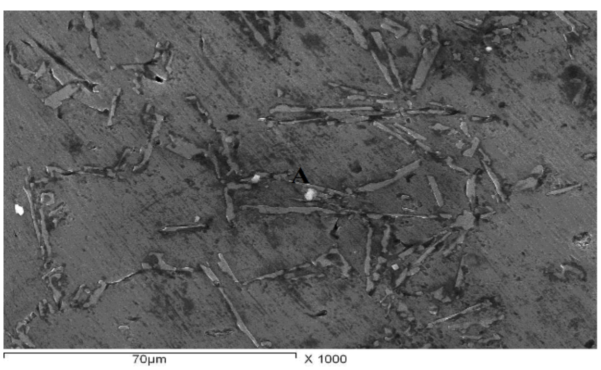
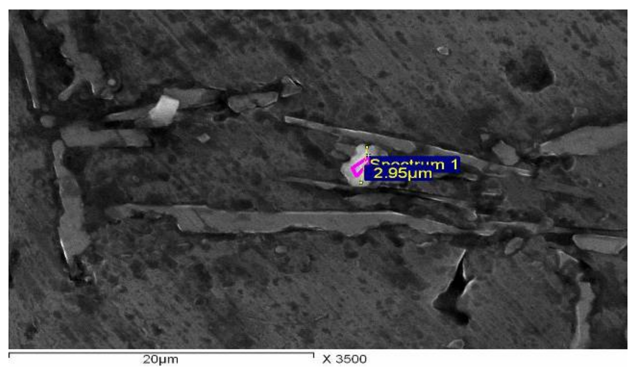
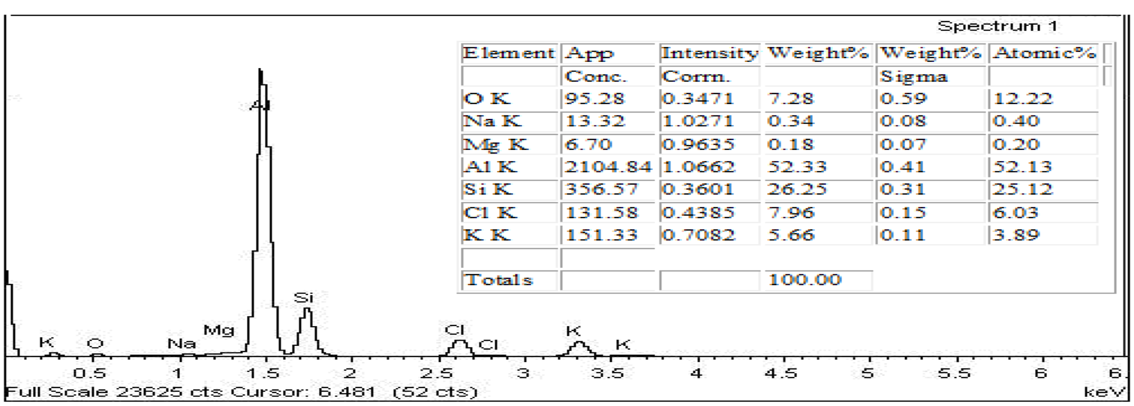


Figure 4(a): SEM analysis for Albite distribution into the A356 matrix alloy



Detail [A]

Figure 4 (b): Albite particle measurement



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
O K	95.28	0.3471	7.28	0.59	12.22
Na K	13.32	1.0271	0.34	0.08	0.40
Mg K	6.70	0.9635	0.18	0.07	0.20
Al K	2104.84	1.0662	52.33	0.41	52.13
Si K	356.57	0.3601	26.25	0.31	25.12
Cl K	131.58	0.4385	7.96	0.15	6.03
K K	151.33	0.7082	5.66	0.11	3.89
Totals			100.00		

Figure 4 (c): EDAX analysis for (A356-3%Albite) MMC.

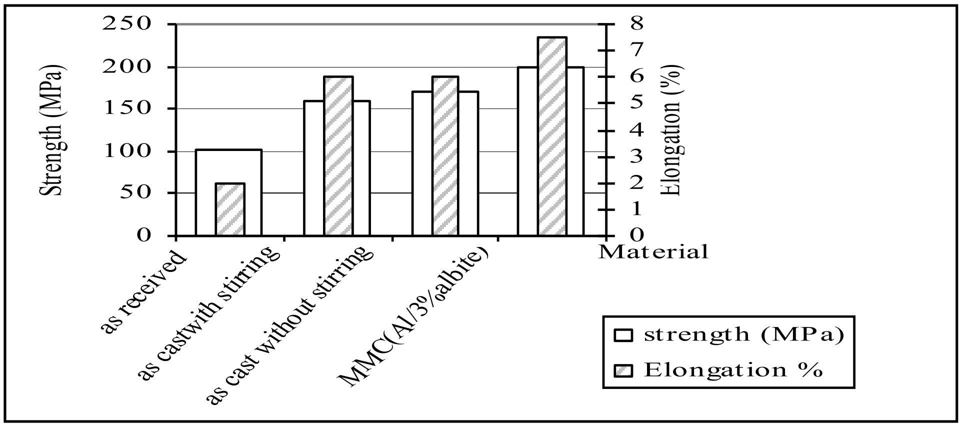


Figure 5: Tensile strength and elongation percent for tested materials

Figure 6: Pictorial photo of (A356-3% Albite) MMC's broken tensile sample.

3.3 Compression properties

Figure (7) shows the graph of compression yield strength and yield strain. Each result is an average of four readings. While the typical compression stress versus the relative strain in both elastic and plastic zones for (A356-3% Albite) MMC is presented in figure (8), whereas, the whole produced materials from A356 alloy have the same trend.

In the present investigation the compression properties comparisons are made among the tested materials through the yield strength values (YS). As indicated from Figure (7), the average YS changed from 152 MPa for the commercial received A356 alloy to 190 MPa for as cast alloy to 195 for stirred alloy to 229 MPa with 3% Albite addition. While the strain changed from 7 for the A356 received alloy to 8 for both as cast and stirred alloy, and 11 % with Albite addition. These data shows clearly the compression yield values, (stress or strain) has been increased in both as cast and cast stirred alloy over the commercial received one. Also addition improvement was achieved with adding Albite particles to the alloy, to reach 150 % for YS and 157 % for elastic strain of that of commercial alloy.

On the other hand, the ultimate compression stress (UCS) may be determined at the end of plastic stage, which represents the start of hair cracks at the lateral surface. For more illustration the experimental compression data (Figure 8) revealed UCS of these materials at 30 % strain with values; 270, 320, 305, and 314 MPa for the A356 commercial alloy, the casting one , the mechanically stirred casting alloy and the casting MMC material, respectively. These results indicate slightly change of UCS with adding Albite ceramic to the unreinforced stirred alloy. Ramesh [4], obtained marginal increase in compression value at plastic stage too.

On the macro observation, an early appearance of surface cracks in commercial alloy has been detected; it may be due to coarse dendritic structure and brittle coarse eutectic Si phase (Figure 4.a), beside, including macro porosity in this alloy. Regarding (A356-3% Albite) MMC, high plastic strain (65%) has been obtained without surface damage. This very interesting result, as it is an indicator for possibility of subjecting the fabricated (A356-3% Alabite) MMC to secondary forming processes that consider one of the most difficult problems encountered applicability of MMCs materials.

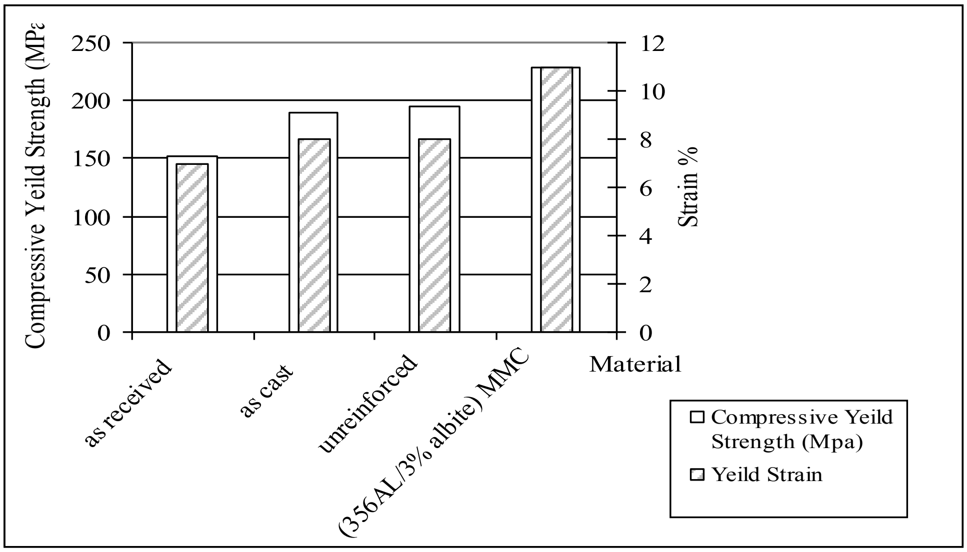


Figure 7: Compressive yield strength and strain for tested materials

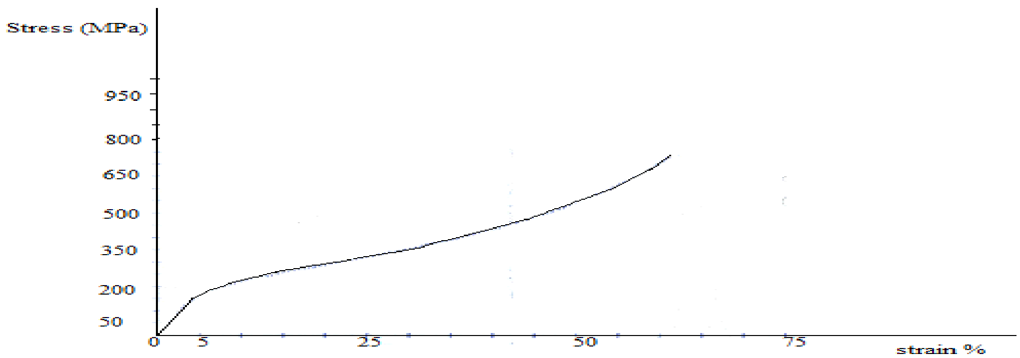


Figure 8: Typical curve of compression strength of (A356-3% Albite) MMC

3.4 Hardness

Vickers hardness results are shown in figure (9). Each result is an average of 7 readings. Slight increase in HV of (A356-3% Albite) MMC is indicated, more than unreinforced alloy (4%) where as hardness test is conducted on macro-hardness scale (measuring area can't be focused onto stiffer phase). **Ramesh** [4], reached to 47% increase in BH of (A6061- Albite) MMC than unreinforced alloy on the microhardness scale, this contradiction may be due to using large particle size (90-150 µm) in his study and hence existence of large surface area of hard phase. Thus it is included that using MMC with coarse ceramic particles convenes wear applications rather than those of fine sizes.

3.5 Impact

The impact strength of aluminum die casting alloys is a critical mechanical property needed by designers. Currently, no reliable impact strength data for die cast aluminum alloys is available in the open literature [13]. In the present investigation, un-notched samples have been selected rather than V-notched that it gives more realistic indicator about material toughness beside this way fits A356 alloy that behaves as a semi-ductile material. Figure (10) shows the graph results of impact test for Charpy un-notched samples, each result is an average of four readings. Figure (10.a) indicates that the average absorbed energy changed from 6 J for the A356 commercial received alloy to 20 J for as cast alloy in SSM, to 25 J with applying mechanical stirring into cast alloy to 28 J with 3% Albite addition to the cast A356 alloy. These results revealed the dramatic effect of SSM processing technique on material toughness, beside the obvious effect of applying mechanical stirring during casting. The impact strength of A356 commercial alloy agrees with that obtained by Jenaball *et al.*[14], as they reached impact strength of A356 alloy with 5.7 to 6.2 J for Charpy un-notched sample according to similar cross section of casting ingot. While Shueiwan and Shyh-Ming [10] recorded impact energy of 1.22 J for V- notched sample.

Shueiwan also showed that the as-cast A356 alloy formed via SSM process absorbs 11.5Joule for V-notched sample which is very high relative to ASTM specification value (3.8 J for A356-T6) as he stated.

On the other hand, as indicated from impact results, reinforcing A356 alloy with 3% Albite particles added more toughness to which, to reach 350% of that of received commercial one. Pictorial photos of broken impact samples as in figure (10.b) show the obvious variation of fracture bending degree among them. Higher bending degree indicates higher material ductility and hence asserted the obvious increase in toughness.

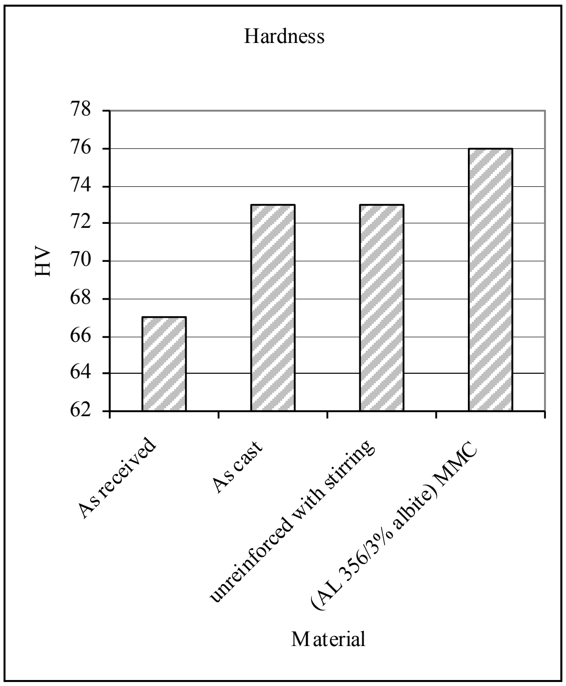
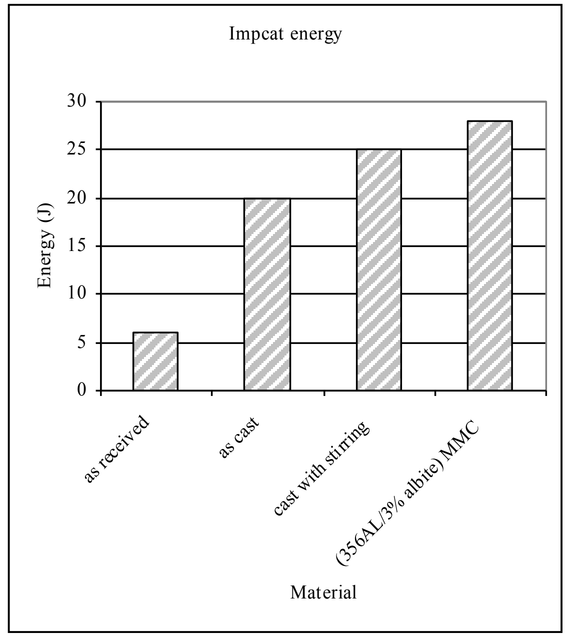


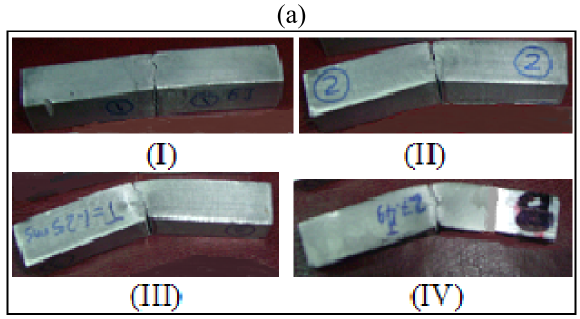
Figure 9: Hardness graph for tested materials

3.6 Fractograghy

Morphological analysis of the fracture surface shows the importance of alloy microstructure in the cracking process. Decohesion mechanism and crack path are strongly influenced by the volume fraction and morphology of the silicon precipitates in Al-Si alloys [15]. The fractograph images of samples are shown in Figs. 11 and 12 for both tensile and impact samples respectively. Tensile fractograph image and ESAX of (A 356 -3%Albite) MMC (Figure 11) indicated good binding between matrix alloy and Albite particles and mixed (cleavage-dimple) fracture is shown in the composite material. **Ramesh** [4], examined the fracture surface of A6061 alloy reinforced with 4% coarse Albite particles, cleavage-brittle fracture is seen from SEM tensile fractograph study.



(a)



(b)

Figure 10: (a); Impact energy for tested materials and (b); Pictorial photos of broken impact samples for (I); As received, (II); As cast A356 alloys, (III); Unreinforced stirred alloy and (IV); (A356-3% Albite) MMC materials.

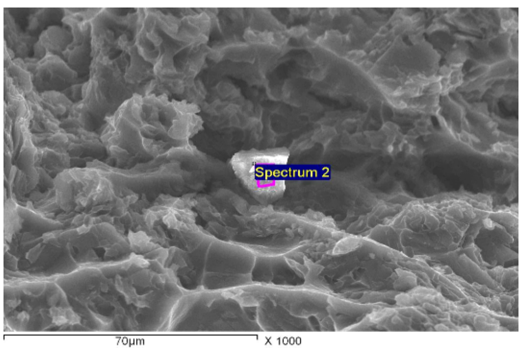
Impact SEM fractographs of produced materials as they are seen in figure (12), the Interdendritic fracture is clear in as received commercial A356 alloy (Figure 12.a) which indicated undergoing this material shrinkage porosity. It's most probably due to coarse dendritic structure that given rise due wide solidification range, as it was cast at fully liquid state. On the other hand, transcrystalline fracture of weakly-developed surface is found in as cast alloy (Figure 12. b) where as the sharp edges of Si are preferred crack initiation sites [10,15] and as a result brittle fracture surface encountered. While bands of micronecks of the aluminum solid solution implies cleavage planes of the brittle fracture between them are obvious in figures (12.c) and (12.d) for both unreinforced stirred A356 alloy and (A356-3% Albite) MMC respectively. Małgorzata [15] explained, that a plastic deformation could take place in the α -aluminum solid solution resulting in the bands of the dimples formation which can be a result of the mixed mechanism of fracture. This kind of fracture forms in most cases in alloys of modified silicon morphology (in liquid or solid state). In which Si eutectic network is partially broken. The brittle Si particles are surrounded with a relatively soft matrix and sometimes isolated. Due to the strong cohesion at the interfaces between α -aluminum and silicon, the matrix is deformed under local active stress. In the present investigation, the modification in the structure of (A356-3% Albite) MMC is attributes to applying mechanical stirring during casting, beside, dispersions existence which changed the columnar dendritic structure to equiaxed dendrite forms as it is obvious from the optical microstructure examination (Figure 3.d).

4-Conclusion

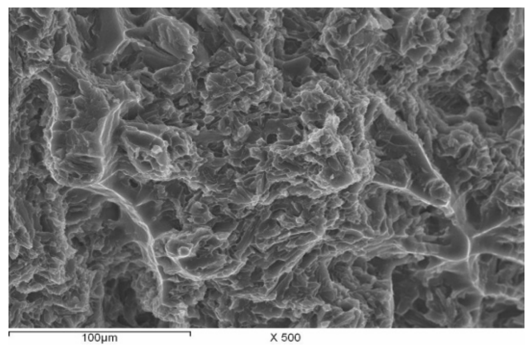
1- Proper way of material processing is essential to achieve most of its potential. Where as, production of A356 alloy via SSM route exhibited dramatic change in mechanical properties rather than that produced by fully liquid casting, further economic benefit. As, 65.8 and 316 % increase of UTS and toughness respectively were achieved in A356 stirred alloy by SSM of that of as received alloy.

2-(A356-3%Alabite) MMC can be fabricated successfully via stir casting technique in SSM condition as a way for overcoming extremely poor wettability of Albite ceramic.

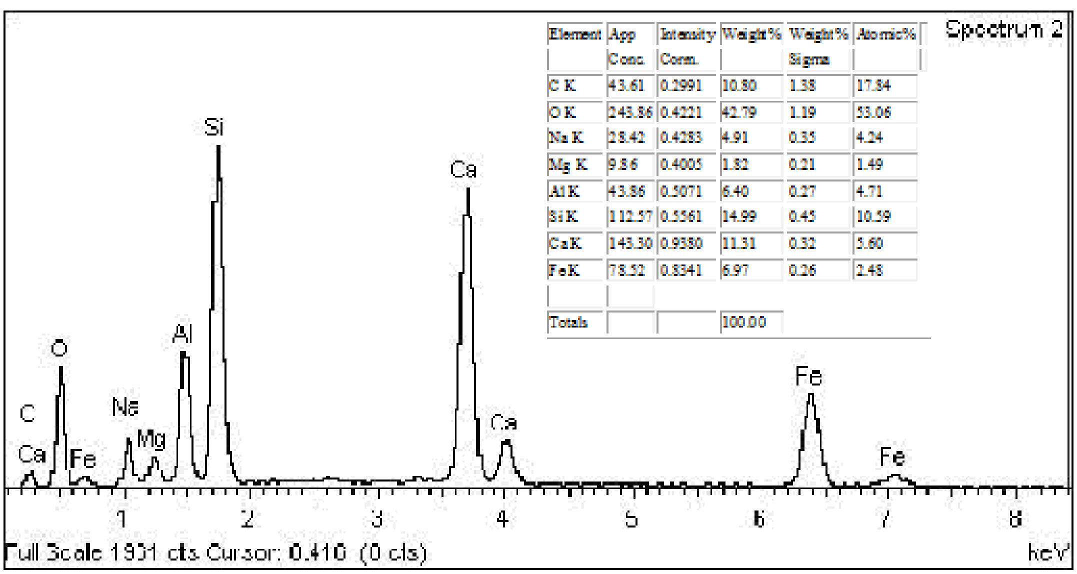
3-Adding Albite to A356 alloy has significantly increased the tensile strength as well as elongation percent with 18% and 25% respectively.



(a)



(a')



(b)

Figure 11: (a) and (a'); tensile fractography for two magnifications, and (b); EDAX of (A356-3% Albite) MMC material.

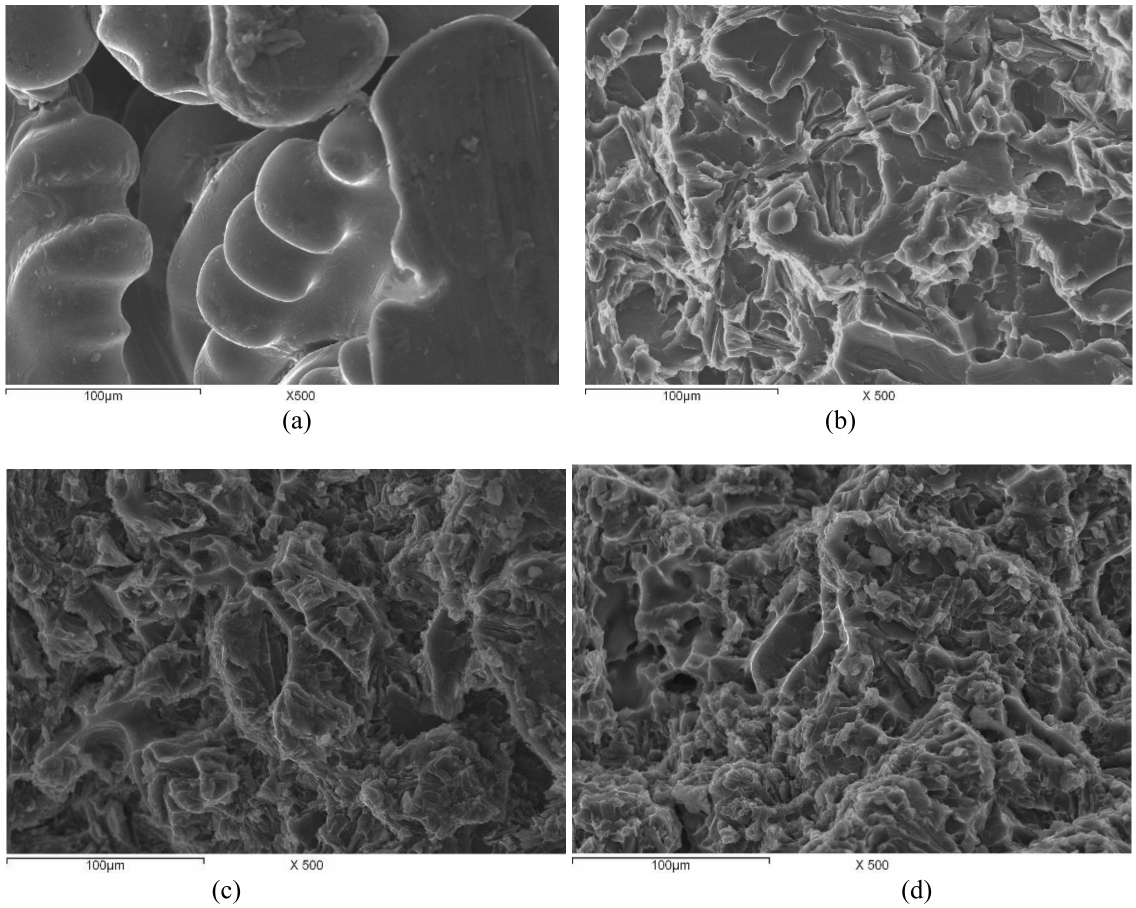


Figure 12: Impact fractography of (a); As received, (b); As cast,(c); unreinforced stirred A356 alloys and (d); (A356-3% Albite) MMC materials.

4- Higher compression yield strength and relative elastic strain with 17 % and 37.5% in sequence were achieved in (A356-3%Alabite) MMC than that of the unreinforced alloy, while marginal increase in compressive strength in plastic zones has been obtained.

5-High formability of (A356-3% Albite) MMC is proved from compression results as a great benefit of produced composite.

6-The 3% addition of Albite ceramic to the A356 alloy has improved the fracture toughness by about 12 % while a slight increase in hardness was observed as a result of existence Albite dispersions into the matrix alloy.

7-Light weigh (2.6 g/cm^3) and un-reactive at elevated temperature make Albite a promising dispersion ceramic for producing MMCs from Al alloys, so comprehensive studies must be exerted to develop production of MMCs with high fraction weight of Albite ceramic to detect more advantages.

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