DEVELOPMENT OF ALUMINIUM BASED METAL MATRIX PARTICULATE COMPOSITES (MMPC) REINFORCED WITH ALUMINA USING STIR-CASTING TECHNIQUE

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ABSTRACT

This work attempts to develop Aluminum-Alumina Metal Matrix Composite of Particulate brand for the Nigerian Economy. Various equipment and tools were designed and fabricated for the purpose of synthesizing Al-Si/Al_2O_3 composite by Stir casting technique. Series of trial experiments were carried out to establish the optimum processing parameters. The strongest among the successfully developed Al-Si Al_2O_3 composite was the one reinforced with 5 wt.% particles having the Ultimate Tensile Strength (UTS) and yield strength values being 180.85MPa and 150.28MPa respectively. The produced composites were very brittle with percentage elongation close to zero.

1.0 INTRODUCTION

Metal-Matrix Composites (MMC) have received attention over the past decades as one of the substitutes for iron and steel. Metal Matrix Composites (MMC) are relatively new class of engineering materials in which reinforcement material is incorporated into a metal matrix to improve its properties. Broad range of composites in the class of MMPC has been produced by stir casting over the years and components fabricated by this process have found various applications. Astounding success has been recorded in the production of various automobile components from MMPC. Piston is one of the first automobile components to be produced from MMPC [1]. Other components of automobiles presently at various levels of incorporation include cylinder liners, piston rings, connecting rods and engine block. The advantages recorded from incorporating these parts include reduced wear, anti-seizing properties, cold start, lightweight, fuel conservation and improved efficiency.

As early as 1968, Stir-Casting method was successfully used in producing Aluminium-Alumina composite at the Indian Institute of Technology, Kanpur India. [2]. Other developing countries such as China, Singapore, Iraq, South Korea and others also carried out substantial research into this production technique [3]. African countries such as Egypt and Libya have also made modest contribution to composite materials research. In the quest by Nigeria to achieve technological breakthrough and to have an economy less dependent on importation, it is important that the country should take a bold step towards the development of local technology to produce new engineering materials such as MMC.

The major objective of this research work is the development of the indigenous technology for producing Al-Si/Al_2O_3 composite by stir casting technique, bearing in mind the available resources and the existing technological base of Nigeria nation. Various equipment and tools were designed and fabricated (Fig. 1) for the purpose of synthesizing Al-Si/Al_2O_3 composite by stir casting technique. Series of trial experiments were carried out to establish the optimum processing parameters such as 4-blade impeller stirrer, 1000rpm stirring speed, stirring temperature range of 740 –760 ^{0} C and a varying stirring height. The strongest among the successfully developed Al-Si/Al_2O_3 composite was the one reinforced with 5 wt.% particles having the ultimate tensile strength (UTS) and yield strength values being 180.85MPa and 150.28MPa respectively. The produced composites were very brittle with percentage elongation close to zero.

2.0 LITERATURE REVIEW

2.1 Fabrication Methods and Associated Problems

There are numerous fabrication methods that have been invented for specific composites. The process of unification of these methods gives rise to three broad methods: solid phase, powder and liquid phase methods. Liquid phase methods are good for fabricating various composite materials. It is, however, characterised by high reactivity of matrix/reinforcement system [2]. However, the knowledge and experience accumulated in the field of controlling the interaction between the matrix and the reinforcement by alloying the matrix and modifying the fibre surface, as well as the development of wide spectrum of fillers, has allowed liquid phase technology to be applied to a wide range of systems. The simplest of liquid phase method is Dispersion method. Stir casting is one of the variants of dispersion method. One of the advantages of using stir-casting method in MMPC production is the possibility of using conventional foundry equipment. Thus, standard stir-casting equipment comprises the melting unit and the stirring mechanism. The major difficulties in fabricating aluminium-ceramic composites through stir-casting techniques are: 1) Absence of wetting between molten metal and ceramic particles at temperatures used in conventional foundries. 2) Segregation of dispersed particles in the melt and in the solidified casting due to differences between aluminium and ceramic particles[4].

Crucial factors in the transition of ceramic particles from non-wetting to wetting state are: operating temperature, alloying of the matrix and coating of the reinforcement. Attainment of threshold temperature at which wetting is achieved, could be a precondition for wetting. Threshold temperature is attained by preheating the reinforcement materials and overheating the melt to a predetermined degree. Chemical activation of reinforcement particles was experimented by Li et. al [5] to enhance wettability. Warrier et. al. [6] suggested that improved wettability could be attained if the contact between the reinforcement and the matrix is gradual. This could be achieved by wrapping of the reinforcement in aluminium foil was practised for SiC particles. Do-Suck-Han et al. [7] observed that wettability of materials depend on the wetting angle. The particulate materials with the least angle of wetting are expected to exhibit the best wettability.

Many researchers [4,7 and 10] have shown that alloying of the molten metal could enhance wetting considerably. This is possible where such alloying element decreases the surface tension of the melt. reduces the interfacial energy and promotes the chemical reaction between melt/ ceramic interfaces. Such alloying elements such as silicon, magnesium, copper, titanium, zinc, lead or bismuth have been used to enhance wetting of ceramic particles by molten matrix of aluminium.

2.2 Stir-casting Equipments and Accessories

One of the advantages of using stir-casting method in MMPC production is the possibility of using conventional foundry equipment. Thus, standard stir-casting equipment comprises the melting unit and the stirring mechanism. The melting equipment used are mostly electrical furnace of resistance and induction heating type. While Hanumanth and Irons [8] used a 10kW capacity resistance furnace with clay graphite crucible of 0.3m average diameter, Young-Ho-Seo and Chung-Kil [9] employed a small graphite crucible whose diameter ranged between 45mm and 63mm. A smaller 60g-capacity crucible from MgO with the internal diameter of 38mm was used by Kobashi and Choh [10]. Clay, alumina and SiC are other materials that have been used for the crucible of the melting unit. [5, 11]. The mass of molten metal used ranges between 60g and 450g. The melt produced has also been subjected to various treatments such as fluxing, degassing, vacuum treatment, argon-gas injection and nitrogen-gas treatment.

The stirring mechanism generally consists of a motor, a driving shaft and an impeller. The motor employed is usually a variable speed type and various speeds ranging between 300 and 1250 rpm have been experimented by various researchers[2,3,4,7and 8]. An optimum stirring speed of 550 rpm was suggested although with limitation [8]. The fundamental basis for the choice of the speed is the ability to create vortex in the body of the metal-matrix. The impeller shaft and blade were made from various materials such as graphite and alumina and rarely coated steel. The construction of the impeller blade must ensure the dragging the reinforcement particles into the body of the molten metal, ensuring wetting of the particles with the matrix while at the same time preventing the floating or sinking of the reinforcement particles. A pitched-blade turbine impeller was successfully used by Hanumanth and Irons [8]. The most common type of impeller is the two-blade type. However, their performance was adjudged unsatisfactory because they could not ensure, adequately, intimate contact between the particulate materials and the molten aluminium. Abdul-Azeem et. al.[11] recommended a four-blade impeller made from clay-coated mild steel. This impeller provided a shearing and wiping action, which effectively homogenised the mixture.

The use of the above impellers considerably raises the level of porosity in the prepared composite. Thus an improved impeller, which suppresses the vortex motion and enhances turbulent mixing, was designed by Duralcan [12]. The fluted stirrer of Duralcan leaves the top of the melt relatively quiet and prevents exposure of fresh liquid alloy to the environment resulting in decreased porosity. Such fluted stirrer can only find use when large volume of metal is involved. [13]

In order to ensure gradual and uniform introduction of reinforcement particles, a funnel shaped particle injection chamber was utilised by Young-Ho-Seo [9]. Preheating the particles has been practised by various researchers. Alumina particles were preheated to 500 °C by Abdul-Azeem et. al. [11], Li et al. [5] used 800°C preheating temperature while Surappa and Rohatgi [4] subjected the same particles to 900°C preheating for 1 hour period before the introduction into the matrix.. Preheating of the impeller was also practised to avoid chilling of the metal in the area surrounding the cold impeller.

3.0 EXPERIMENTAL PROCEDURE

3.1 Metal Melting

25 kg of the investigated aluminium silicon alloy was melted in a gas-fired furnace equipped with a graphite crucible and a blower and superheated to a temperature of 760 °C. The temperature was measured using immersion pyrometer (Migert type). Since the alloy used was primary alloy, the use of fluxing materials was not required.

3.2 Reinforcement Incorporation

Five samples of silica reinforcement, weighing 2.5g, 7.5g, 12.5g, 20.0g and 25.0g, were weighed and preheated at 1000°C for 1 hour to enhance incorporation and wetting. As previously established, a speed of 1000 rpm were chosen, while four-blade impeller was used. The height of the stirring was made variable for effectiveness. Molten metal was taken from the bulk-

1 – Electric Motor
2 – Stirrer rod
3 – Crucible Holder
4 – 4-blade Impeller
5 – Furnace Lid
6 – Steel Shell
7 – Steel Crucible
8 – Alumina Refractory
9 – Ceramic Insulator
10 – Steel Support
11 – Electric Connector

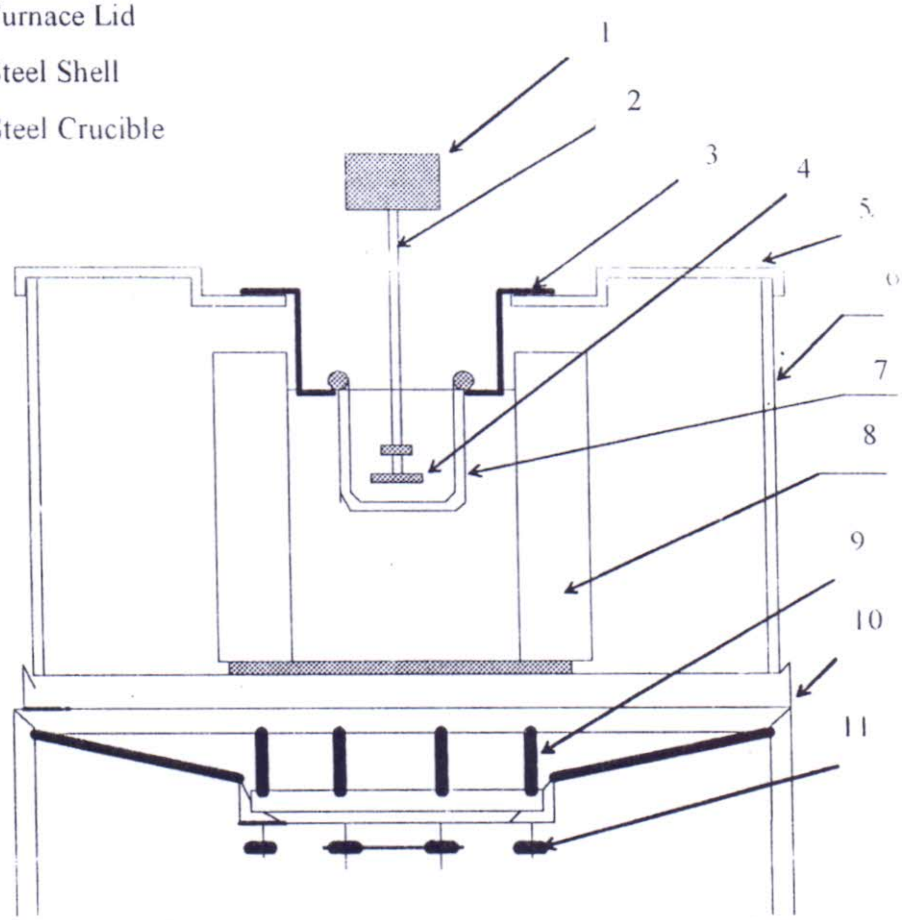

Figure 1: Schematic Drawing of Apparatus used for Stir-casting of Metal Matrix Particulate Composites (MMPC)

melting furnace and poured into the preheated crucible of the stir-casting equipment (Figure 1) up to the 250-gramme mark. The mixer with the impeller blade fixed was switched on and gently lowered into the molten metal. The position of the stirrer was adjusted inside the crucible until a vortex was formed. The reinforcement particles inside the injection funnel were then gradually and smoothly introduced into the molten metal.

The stirring continued for about five to ten minutes after the completion of particle introduction. The stirrer was raised at the end of mixing. Digital thermocouple was used after the stirring to ensure that correct pouring temperature of 760 °C was attained. The prepared composite was poured into the prepared mould immediately.

3.3 Casting of Test Specimen

The pattern employed for the casting was a wooden British Directorate of Technical Development (DTD) test bar with a cylindrical portion having a diameter of 25mm and a funnel – shaped riser which served as a sprue having a maximum diameter of 30mm. After the temperature of the prepared composite was recorded, the molten composite was then poured into the previously marked sand mould to enhance easy identification of the sample. Three specimens were cast for each melt to provide samples for tensile test, hardness test and metallographic examination.

3.4 Evaluation of Mechanical Properties of Specimens

Tensile Testing: Tensile test was performed under uniaxial tensile loading on specimen machined to a standard geometry (d = 5mm, l_c = 45mm). The tensile test was carried out on Hounsefield Tensometer equipped with data acquisition system, which supplies the stress – strain curve during testing at room temperature environment.

Hardness Test: The specimen for hardness test was obtained by cutting the DTD cast specimen into two equal halves, using hacksaw. The flat surface obtained was subsequently smoothened with files. The samples were then polished with emery cloth, nylon cloth and micro cloth using one micron alumina polisher.

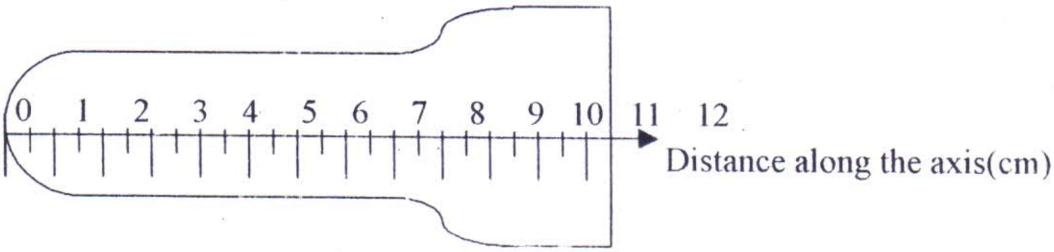

Figure2: Section of the test bar showing the points at which hardness test was taken.

The polished specimen was thereafter subjected to Brinell hardness testing at a uniform interval along the whole length of the specimen (Figure 2) using 1mm diameter indenter and an applied force of 49.05N.

Metallographic Examination

Specimen for microstructural analysis was the half piece of the one used for hardness test. The specimens are polished on a series of emery paper in water and finally on sylvet clothe using alumina abrasives. Specimens were etched with 0.5% HF and examined under optical microscope. Microphotograph of specimens were taken at strategic locations at 100′ magnification.

4.0 RESULTS AND DISCUSSION

4.1 Mechanical Properties Of Al-Si/Al_20_3 Composites

Strength: The results obtained from the tensile test carried out to determine the tensile yield strength(s_o), the ultimate tensile strength (s_u) and the percentage elongation are as presented in Fig.3 With the exception of composite reinforced with 5 wt,% reinforcement, the general trend of the graph indicates that both the yield strength and UTS decrease with increase in proportion of reinforcement. The percentage elongation also showed a substantial decrease compared to the unreinforced sample (0 wt.%). The conclusion of various researchers on the behaviour of Al-Si/Al_2O_3 with increase in the reinforcement varies greatly. Abdul Azeem et. al., [11] concluded that only yield strength increases with increased reinforcement, while UTS and percentage elongation decreases in stir-cast Al-Si/Al_2O_3 composites. The behaviour of the composite was directly connected to the alloying element of the Aluminium matrix by Surappa [4]. He concluded that while UTS increased with the increase in reinforcement fraction in pure aluminium, UTS decreased with reinforcement fraction in Al-Si alloys. The result obtained in this work is corroborated by the position of Surappa. A consistent strengthening of Al-Si alloy could not be obtained using stir-casting method if the percentage reinforcement falls below 18 vol.% [14]. If, however, a different production method is used such as Pressureless liquid-metal infiltration process [15], or other alloying element such as Mg, Mn or Cu is introduced [12], then substantial improvement in strength compared with unreinforced alloy could be attained.

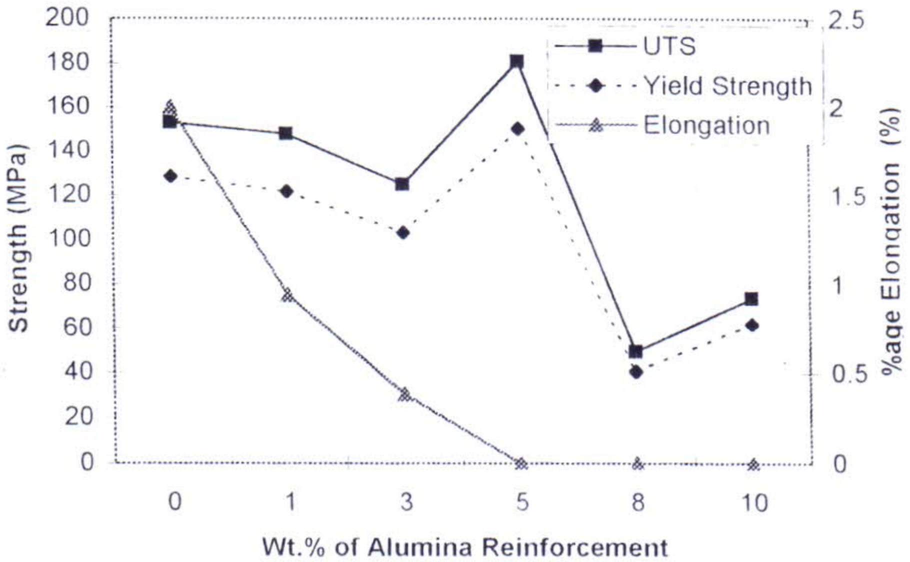

Figure 3: Variation of Mechanical Properties of Al-Si/Al_2O_3 Composites.

The improvement in strength observed in composite is attributable to the behaviour of reinforcement particles as barriers to dislocations. The increase in proportion of reinforcement increases the number of barriers to dislocation movement and thus increasing the strength [15]. Equally important is the distribution of pores in the composite which reduces the strength parameters. The strength of the interface also determine the effectiveness of reinforcement particles. Where the interface is weak, the dislocation will propagate across the particle/matrix boudaries. Consequently, the reinforcement particles will not have the desired effect on the composites [15].

Generally, the compressive strength of both pure Al and Al alloys increased with addition of alumina particle, irrespective of the production technique [4].

The percentage elongation of the composite showed a considerable decrease compared to the unreinforced alloy. The considerable brittle nature of the produced composite, compared to that of the ones produced by other researchers is due to the fact that no coating or wetting agent is adopted for the reinforcement in this process. Thus, the strength of the interface remains low, making the composite susceptible to brittle failure.

4.2 Hardness of the Developed Al-Si/Al_2O_3 Composites

The result of the hardness test carried out showed improved hardness behaviour in the alumina reinforced composite compared to the unreinforced alloy. While the hardness of the unreinforced alloy was at 38 BHN, the reinforced composite had a hardness value of 69 BHN at the larger portion of the surface area assessed. At different portions of the area, a higher hardness value of 79 BHN was recorded which showed a considerable increase over and above the value of the larger portion of the area. Similarly, a hardness value as low as 11 BHN was noticed at isolated portion close to the sprue area of the test bar.

The zone with hardness value of 69 BHN was representative of the hardness value of composite with 10% reinforcement. This represents an increase of about 82% over the unreinforced alloy. The increased hardness of composites could be attributed to relatively high hardness of Al_2O_3 compared to that of Aluminium alloy.

Composite with 5% reinforcement was characterized by a higher hardness value at some portion of the section, which signifies zone of agglomeration of reinforcement particles while low level of hardness was generally observed at the zone close to the sprue base. This could be attributed to the higher concentration of voids and cavities in this zone.

4.3 Metallographic Studies of Al-Si/Al_2O_3 Composites

The Al-Si alloy used is a binary alloy characterized by good casting characteristics such as small shrinkage, excellent fluidity, good gas permeability and low tendency to form crack after solidification. The microstructure of the Al-Si alloy is shown in Plate 1. It consists of aluminium matrix containing needle-like shape of eutectic silicon particles in the dendritic region.

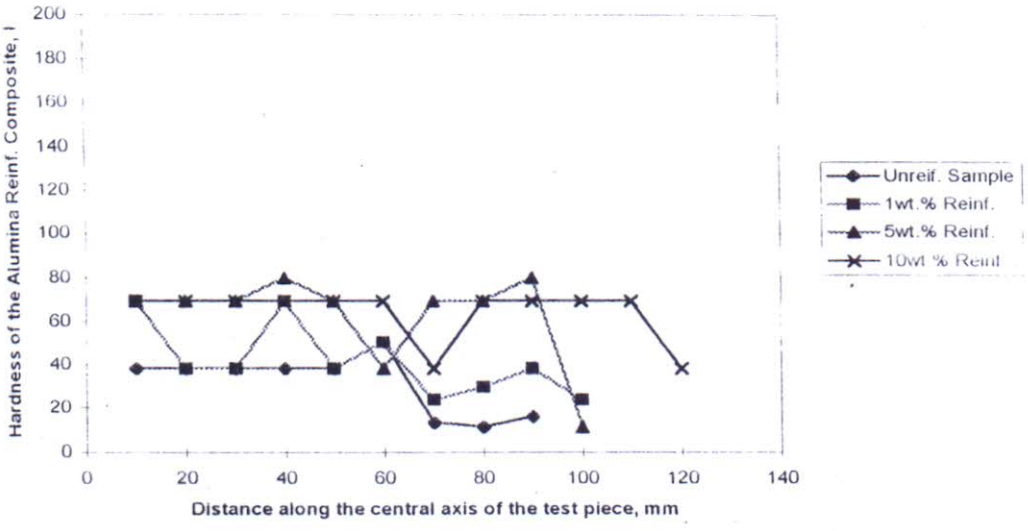

Fig. 4: Variation of Hardness Characteristics of Alumina Reinforced Composites (1wt.%, 5wt.% and 10wt%).

The photomicrograph of the composite reinforced with 1 wt.% alumina is presented in Plate 2. The sparse distribution of the reinforcing alumina particles in the body of the matrix is quite noticeable. The gradual thinning down of the particle distribution from the bottom to the top of the test bar was observed as the specimen was browsed from the bottom portion of the cast test bar.

The developed composite with 3 wt. % of alumina particles is presented in Plate 3. The occurrence of penumbra around the reinforcement is illustrative of possible reaction between the matrix and the reinforcement, which also enhances strength. The Al-Si/ Al_2O_3 composite loaded with 5 wt. % of alumina particles is shown in Plate 4

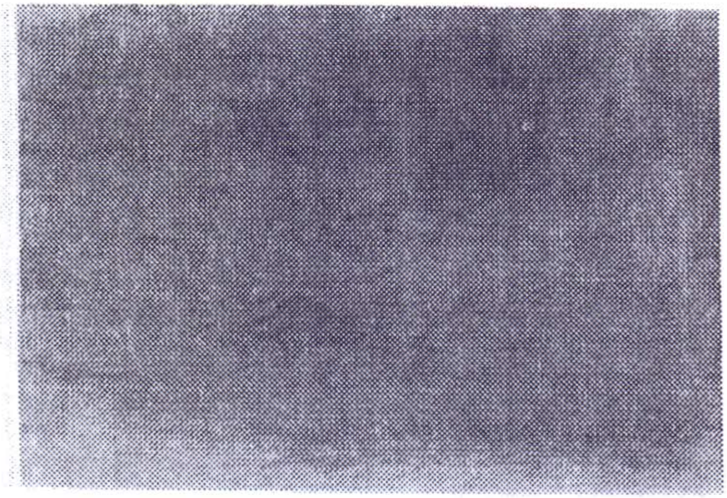

Plate 1:Optical Microphotograph of the Aluminium-Silicon Alloy Matrix (LM6) containing 12% Silicon. (The light background shows the á-aluminium while the darker zone shows the needle-like shaped eutectic silicon particles).X 100

Plate 2: Microphotograph of the Aluminium-Silicon Alloy Matrix (LM6) reinforced with 1% Alumina. (The non-uniformity in the dispersion of the reinforcing particle is noticeable in the section covered). X 100

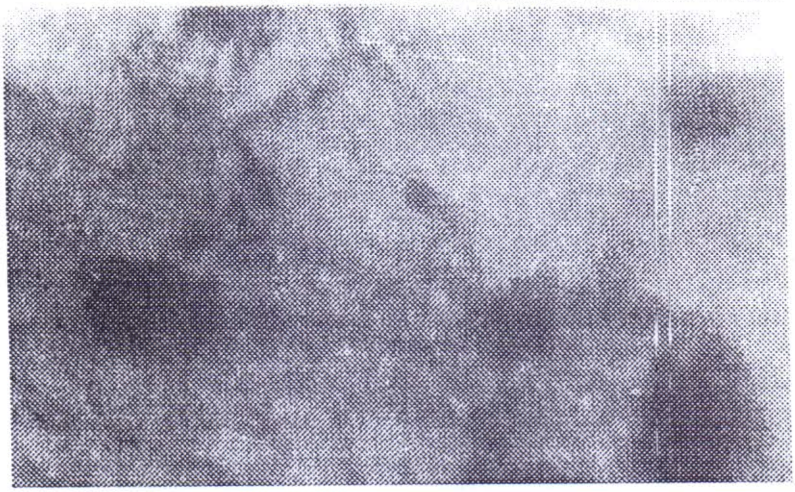

Plate 3: Microphotograph of the Aluminium-Silicon Alloy Matrix (LM6) reinforced with 3% Alumina. (The increase in the incorporated fraction of the reinforcement particles coupled with a strong bond between matrix and reinforcement phases could be responsible for increased strength observed in this sample). X 100

Plate 4: Microphotograph of the Aluminium-Silicon Alloy Matrix (LM6) reinforced with 5% Alumina. (The increase in the proportion of reinforcement particles resulted in the need for vigourous and prolonged stirring thus leading to possible increase in porosity of the produced composite). X100

Conclusion

An attempt has been made to develop Al-Si/ Al_2O_3 composites and the properties and the microstructures so obtained have been studied. From the level of success attained in this work, the following conclusions could be drawn:

i) The appropriate parameters for the synthesis of MMPC by Stir casting include the use of four-blade stirrer at 1000rpm. A temperature of 760 ^{0} C and a varying height of stirring was most suitable for different types of composites developed in this work.

ii) The highest strength (UTS) recorded for the developed Al-Si/ Al_2O_3 was 183 MPa for alloys reinforced with 5wt.% of Al_2O_3. This represents an increase of about 17% above the unreinforced alloy.

iii) The ductility of the developed composites reduced considerable with increase in the fraction of reinforcement. The value of ductility tends towards zero at higher reinforcement ratio.

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