THE DEVELOPMENT OF Al-5%Cu/GRAPHITE PARTICULATE COMPOSITES FOR ENGINEERING APPLICATIONS

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BY

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A THESIS SUBMITTED TO THE POSTGRADUATE SCHOOL AHMADU BELLO UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIRMENTS FOR THE AWARD OF MASTER DEGREE IN METALLURGICAL ENGINEERING

DEPARTMENT OF METALLURGICAL AND MATERIALS ENGINEERING,

FACULTY OF ENGINEERING AHMADU BELLO UNIVERSITY,

ZARIA, NIGERIA

APRIL, 2010

DECLARATION

I declare that the work in the thesis entitled 'The development of Al-5%Cu/Graphite Particulate Composites for engineering applications' has been performed by me in the Department of Metallurgical and Materials Engineering under the supervision of Drs. O. Aponbiede and T. Ause.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at any university.

…… …….. ……

Name of Student signature Date

CERTIFICATION

This thesis entitled "THE DEVELOPMENT OF AL-5%CU/GRAPHITE PARTICULATE COMPOSITES FOR ENGINEERING APPLICATIONS" by Shehu Umar meets the regulations governing the award of the degree of Master of Science of Ahmadu Bello University, Zaria, and is approved for its contribution to knowledge and literary presentation.

…… ……..

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DEDICATION

This thesis is dedicated to the Almighty who deserves our total loyalty for indeed “my prayer, my Sacrifice, my living and my dying are all for Allah, the Lord of the Worlds. He has no partner and of this I have been commanded and I am the first of those who submit” Q6:162-163.

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ABSTRACT

A method of preparing cast aluminium alloy – graphite particulate composite using uncoated graphite with the addition of 1wt% magnesium to aid wettability was studied. The method consists of introducing and dispersing uncoated but pre-treated graphite particles in aluminium alloy melt and casting the resulting composite melts in suitable moulds. The graphite was pre-heated to 400^{o}C in air for 2 hours just prior to dispersion in the melts. Al-5%Cu and 1%Mg by weight with various additions of graphite particles with 1,3,5,7 and 9wt% were produced using the stir casting method. The resulting materials were solutionized at 520^{o}C for 2 hours and quenched in warm water at 50^{o}C followed by ageing at 100^{o}C, 200^{o}C and 300^{o}C at various ageing times ranging from 60-360 minutes. The properties such as density, apparent porosity, impact strength, hardness, yield and tensile strengths were evaluated. Except for the density and porosity, all other properties were evaluated in both the as-cast and heat treated conditions. The results obtained showed a general decrease in the mechanical properties and a wide scatter indicating some increase and decrease at various compositions of the graphite particles and at various age hardenened temperatures. The wide scatter of results was generally attributed to the behaviour of graphite which is weak and soft acting essentially as porosity in the alloy matrix. The investigation also showed that the composite produced responded to precipitation hardening treatment.

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ABBREVIATIONS

AlMMCs	-	Aluminium Metal Matrix Composites
MMCs	-	Metal Matrix Composites
MMPCs	-	Metal Matrix Particulate Composites
AMCs	-	Aluminium Matrix Composites
Al/Grp	-	Aluminium- Graphite Particulate Composite
Grp	-	Graphite Particulate
PMCs	-	Polymer Matrix Composites
CMCs	-	Ceramics Matrix Composites
UTS	-	Ultimate Tensile Strength
SiCp	-	Silicon Carbide particulate
Al/GrpCs	-	Aluminium graphite Particulate Composites

CHAPTER ONE

1.0 GENERAL INTRODUTION

Many of our modern technologies require materials with unusual combination of properties that cannot be met by the conventional metal alloys, ceramics and polymeric materials. This is especially true for materials needed for the aerospace, underwater and transportation applications. In the aircraft industry, the engineers are increasingly searching for materials with low densities, strong, stiff, abrasion and impact resistant which will not also be easily corroded. Sometimes strong materials are relatively dense and increasing the strength or stiffness generally results in a decrease in impact strength. Therefore, these property combinations and ranges have been and are yet being extended by the development of composite materials (Callister, 1997).

Composite material is not really a new idea; humans have been using composite materials for thousand of years. An example is mud bricks; a cake of dried mud is easy to break by bending, which puts a tension force on one edge but makes a good strong wall where all the forces are compressive. A piece of straw on the other hand has a lot of strength when it is stretched but almost none when crumpled. But if pieces of straws are embedded in a block of mud and allowed to dry, the resulting mud brick resists both squeezing and tearing and makes an excellent building material. In other word, it has both good compressive strength and good tensile strength. Another well-known composite is concrete. Here aggregate (small stones or gravels) is bound together by cement. Concrete has good strength under compression and it can be made stronger under tension by adding metal rods, wires, mesh or cables to the composite thereby creating reinforced concrete(www.science.org.au.htm, 2006).

Composite materials refer to a combination of several materials which provide unique combination of properties that cannot be realized by the individual constituents acting alone. They offer many improvements over the base materials; properties such as bearing, lubricating, damping and machinability can be appreciably enhanced (www.freepatentonline.com, 2007). The idea is that by combining two or

more distinct materials one can engineer a new material with the desired combination of properties e.g. light, strong, corrosion resistant (www.virginia.edu, 2007).

Additionally, where metal alloys (steel, copper, bronze etc) have isotropic characteristics (same in all directions), composites can have very selective directional properties to meet specific applications. Thus, composites are highly engineered materials targeted at specific applications (www.epp.goodrich.com, 2007).

The possibility of taking advantage of particular properties of the constituent materials to meet specific demands is the most important motivation for the development of composites. A composite material is a material that consists of constituents produced via a physical combination of pre-existing ingredient materials to obtain a new material with unique properties when compared to the monolithic material properties

(cimewww.epfl.ch, 2008).

A composite in the engineering sense is any material that has been physically assembled into one single bulk to form a homogeneous material. The resulting material would still have components identifiable as the constituents of the different materials. One of the advantages of composite is that two or more materials could be combined to take advantage of the good characteristics of each of the materials (www. Mech.utah.edu, 2006).

In the past ten years, materials R& D has shifted from monolithic to composite materials adjusting to global need for reduced weight, low cost, quality and high performance in structural materials. During the past 40 years, materials design has shifted emphasis to pursue light weight, environment friendliness, low cost, quality and performance. Parallel to this trend, Metal – Matrix Composites (MMCs) have been attracting growing interest (Ejiofor and Reddy, 1997). The favourable strength –to- weight ratios and the versatility in design that permit material tailoring to a particular need make composites attractive design materials (Lord and Dutta , 1988).

The main feature of composites, being a very important one for material engineering at the same time, is a potentiality for designing specific sets of properties by means of selecting components and the process for the production of these materials (Braszczynska, 2000)

1.1 AIMS AND OBJECTIVES

The aims and objectives of this research work include:

1. To produce the Al-5%Cu/Grp composite using the stir casting method
2. To assess the influence of graphite particulates in Al-5%Cu alloy matrix using Physical (Density and Porosity), mechanical properties and microstructure as criteria.
3. To assess the possibility of using uncoated and pre-heated graphite particulates in Al-5%Cu alloy by the addition of a reactive metal using the stir casting method.
4. To assess the effect of solutionizing and ageing on Al-5%Cu/Grp Composite

1.2 BACKGROUND OF THE STUDY

Over the years, aluminium and its alloys have been used in a large number of industrial applications. Consequently, AMCs are also being used with improved property. However, the use of aluminium as an antifriction material has been limited due to unfavourable wear. Therefore, to improve the wear resistance, it was proposed that graphite particles should be dispersed in aluminium matrices.

Even with the above suggestion, the main problem associated with it is that the graphite particle is not wetted by the aluminium melt. Hence, for graphite particles to be wetted by the aluminium melt either wettability should be induced or sufficient energy should be supplied for the particles to overcome the energy barrier to achieve proper wetting.

In order to achieve the wetting of graphite particles in aluminium melt, the use of coated graphite particle by either nickel or copper had been employed. But the process is expensive and cumbersome.

Hence, a cheaper and less cumbersome method has been suggested which is by using un-coated graphite by the addition of a reactive metal to achieve the wetting of graphite particles in aluminium melts. This work is based on the possibility of using the stir casting method to produce Al-5%Cu/Gr particulate composites and to evaluate their mechanical properties both in the as cast and age hardened conditions considering the advantageous properties of graphite as a solid lubricant with a wide range of applications with increased wear resistance such as bearings, pistons, piston rings, cylinder liners etc. since one of the advantages of using stir casting method in MMPC production is the possibility of using conventional foundry equipment (Abubakre and Khan,2004).

1.3 SCOPE AND LIMITATION

1.3.1 Scope

The study involves:

1. Producing Al-5%Cu/Gr particulate composite using the stir casting method
2. Carrying out solutionizing and ageing treatments on the produced composite
3. Determining the physical and mechanical properties of the produced composite in both the as-cast and age-hardened conditions
4. Studying the microstructures of the composites produced both in the as-cast and age-hardened conditions.

1.3.2 Limitation

There are various methods of producing Al/Gr particulate composites. These include; the powder metallurgy, squeeze casting, compocasting and liquid infiltration methods to mention but a few. The method adopted in this study is the stir casting method because it has some advantages over the existing ones such as that of the powder metallurgy process. Amongst the advantages of the stir casting method

in the production of MMPC is the possibility of using conventional foundry equipment which is more economical as compared to other methods.

1.4 JUSTIFICATION

There is growing research in the use of AMCs since they offer better properties than their base alloys as well as when compared to the use of cast irons and copper base alloys. Cheaper and more convenient methods of fabrications are being developed. Thus, stir casting method is very attractive in attaining this objective since most of the complexities involved in other fabrication methods are avoided. Conventional foundry equipment can also be employed in the fabrication of AMCs. In addition, the relatively low cost of the process makes it a better option to developing countries like ours.

CHAPTER TWO

2.0 LITERATURE REVIEW

Over the last thirty years, composite materials, plastics and ceramics have been the dominant emerging materials. The volume and number of applications of composite materials have grown steadily, penetrating and conquering new markets relentlessly. Modern composite materials constitute a significant proportion of the engineered materials market ranging from everyday products to sophisticated niche applications. While composite have already proven their worth as weight-saving materials, the current challenge is to make them cost effective. The efforts to produce economically attractive composite components have resulted in several innovative manufacturing techniques currently being used in the composite industry (www.tifac.org.htm, 2007).

2.1 PREVIOUS RESEARCH DONE IN THIS AREA

Metals and alloys with low densities such as aluminium, Magnesium, titanium and their alloys are usually chosen as the matrices of Metal Matrix Composites (MMCs) (Yang and Chung, 1989). One of the primary attractions of MMCs has been their potential for high temperature service (Baghat et al, 1992).

Apart from the emerging economical processing techniques that combine quality and ease of operations, researchers are at the same time, turning to particulate-reinforced aluminium metal matrix composites (AMCs) because of their relatively low cost and isotropic properties especially in those applications not requiring extreme loading or thermal conditions (e.g. automobile components). Also, the processing problems and commercial difficulties associated with continuously reinforced AMCs are contributory to the recent interest in their particulate counterparts; the use of aluminium alloys for the matrix is preferred because of its comparative advantages including low cost and ease of handling (Ejiofor and Reddy, 1997).

As early as 1968, stir casting method was successfully used in producing aluminium-Alumina composite at the Indian Institute of Technology, Kanpur, India. Other developing countries such as China, Singapore, Iraq, South Korea and others also carried out substantial research into this production technique (Rizkalla and Abdulwaheed, 1996). 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 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 MMCs ((Abubakre and Khan, 2004).

2.1.1 Previous Research Done at the Department

Some work had been carried out at the department on AMCs at the postgraduate level. One of such is that of Aigbodion (2007) who reported that aluminium is the most popular matrix for MMCs. This is because aluminium alloys are quite attractive due to their low density, their capability to be strengthened by precipitation, their good corrosion resistance, their high thermal and electrical conductivity and their high

damping capacity. Furthermore, AMCs offer a large variety of mechanical properties depending on the chemical composition of the Aluminium matrix.

Asuke (2008) also carried out a study on the material and stated that one of the limitations of AMCs is that they corrode easily in aqueous environment. In addition, researches have been carried out extensively on the corrosion aspects of the material and common reinforcements such as SiC and Al_2O_3.

2.2 Advantages of composites over metals

The greatest advantage of composite materials is strength and stiffness combined with lightness. By choosing an appropriate combination of reinforcement and matrix material, manufacturers can produce properties that exactly fit the requirements for a particular structure for a particular purpose. Modern aviation, both military and civil is a prime example. The demands made by the industry for materials that are both light and strong has been the main force driving the development of composites. It is common to find wing and tail sections, propellers and rotor blades made from advanced composites along with much of the internal structure and fittings. The airframes of some smaller aircraft are made entirely from composites as are the wing, tail and body panels of large commercial aircraft (www.science.org.au.htm, 2006).

The right composites also stand up well to heat and corrosion. This makes them ideal for use in products that are exposed to extreme environments such as boats, chemical-handling equipment and spacecraft. Another advantage is that they provide design flexibility. Composites can be molded into complex shapes – a great asset when producing something like a surfboard or a boat hull. In genera, composite materials are very durable (www.science.org.au.htm, 2006).

In the defense world, marine composites offer great advantages. Navy ships have historically been made of steel, an ideal material for ship construction being both durable and cost effective. But steel ships rust, requiring constant maintenance while the cost of such maintenance has always been accommodated in defense budgets in the past; today there is significant emphasis on eliminating such costs. Further, the loss of ship availability due to this type of maintenance is considered a major cost penalty because other ships must be added to the fleet to assure availability. The heavy weight of steel ships also places limits on the

speed and increases fuel consumption; heavy ships take a lot of fuel to move. Because warships often have to worry about explosive mines, the magnetic signature of ships is a concern to all sailors. Composites are non-magnetic and make an ideal material for any ship expected to face mine warfare conditions (www.epp.goodrich.com, 2007)

2.2.1 Other benefits of composite include (www.epp.goodrich.com, 2007):

a Strong and stiffer than metals on a density basis

- for the same strength, lighter than steel by 80% and aluminium by 60%
- Superior stiffness-to- weight ratios.

b Capable of high continuous operating temperatures

- up 392.4^0 C in many composites
- up to 302.4^0C with FyreRoc composites,

c Highly corrosion resistant

d Electrically insulating properties are inherent in most composite (depending on reinforcement selected) yet composite can be made conducting or selectively conducting as needed.

2.3 Some disadvantages of composites include (wikipedia.org, 2006):

- They are more expensive
- The fibre-reinforced materials may be difficult to fabricate
- The available experience in use is limited.

2.4 Application of composite materials

The application of composites has increased significantly in recent years and is considered to have revolutionalized product design by offering more tailorable properties and manufacturing possibilities (Verbeek and Pickering, 2007).

Each year, composites find their ways into hundreds of new applications: from golf clubs and tennis rackets to jet skis, aircraft, missiles and spacecraft. Their cost trends are highly favorable, especially when the total cost of fabrication is considered. Composites are used in numerous aerospace and marine applications where weight reduction is the primary purpose (www.epp.goodrich.com, 2007).

2.4.1 Marine Composite Applications

With composite exhibiting excellent resistance to the marine environment, their applications have made good inroads in the marine sector worldwide. Complex configuration and the advantages of seamless hulls were the main driving factors in the development of Fibre Reinforced Plastic (FRP) boats. Racing power-boats employ advanced and hybrid composite for a higher performance craft and driver safety. Major structural elements e.g. deckhouses, hatch covers, kings posts and bow modules appear to be very well suited for FRP construction. Advanced composites materials on vessels have a potential to reduce fabrication and maintenance cost, enhance styling, reduces outfit weight and increase reliability. Potential applications of composite materials for ship are:

Shafting over wraps, Life rails, Handrails, Mask, Stacks and foundations, stanchions, propeller vanes, fans and Blowers, gear cases, valves and strainers, condenser shells (www.tifac.org.htm, 2007).

2.4.2 Automobile and Transportation Industry

The potential for increasing fuel economy by reducing the vehicle's weight has stimulated tremendous interest for composite materials in automobile and transportation industries. As a result, industrially developed countries like Japan are extensively using graphite dispersed aluminium composites for automobile parts where friction is involved (www.drdo.resin , 2008).

2.4.3 Aerospace Applications

The aerospace industry's constant desire to enhance the performance of commercial and military aircrafts is continually driving the development of improved high - performance structural materials. In recent years, Metal-matrix composites (MMC) have emerged as a promising class of materials. Especially, Aluminum composites with their unique thermal properties have enormous space and avionics prospects. Al-matrix composites like Al/SiC have the potential of achieving significant weight and cost savings on aircraft structures. Aluminum is the most attractive non-ferrous matrix material used particularly in the aerospace industry where weight of structural components is crucial. The unique thermal properties of aluminum composites, such as metallic conductivity with

Co-efficients of expansion that can be tailored down to zero, add to their prospects in aerospace and avionics (www.home.att.net ,2008).

Other applications of composites are in chemical industry, electrical electronics, construction, offshore oil and gas industry, consumer and sports goods etc (www.tifac.org.htm, 2007).

2.5 Classification of Composite materials (www.Substech.com, 2008).

Many of common materials (metal alloys, doped Ceramics and Polymers mixed with additives) also have a small amount of dispersed phases in their structures, however they are not considered as composite materials since their properties are similar to those of their base constituents (physical properties of steel are similar to those of pure iron).

There are two classification systems of composite materials. One of them is based on the matrix material (metal, ceramic and polymer) and the second is based on the material structure:

2.5.1 Classification of composites based on matrix material

2.5.1.1 Metal Matrix Composites (MMC)

Metal Matrix Composites are composed of a metallic matrix (aluminum, magnesium, iron, cobalt, copper) and a dispersed ceramic (oxides, carbides) or metallic (lead, tungsten, molybdenum) phase.

2.5.1.2 Ceramic Matrix Composites (CMC)

Ceramic Matrix Composites are composed of a ceramic matrix and imbedded fibers of other ceramic material (dispersed phase).

2.5.1.3 Polymer Matrix Composites (PMC)

Polymer Matrix Composites are composed of a matrix from thermoset (Unsaturated Polyester (UP), Epoxy (EP)) or thermoplastic (Polycarbonate (PC), Polyvinylchloride, Nylon, Polystyrene) and embedded glass, carbon, steel or Kevlar fibers (dispersed phase).

2.5.2 Classification of composite materials based on the reinforcing material

2.5.2.1 Particulate Composites: Particulate Composites consist of a matrix reinforced by a dispersed phase in form of particles.

2.5.2.2 Fibrous Composites

Short-fiber reinforced composites: Short-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of discontinuous fibers (length < 100*diameter).

Composites with random orientation of fibers.

Composites with preferred orientation of fibers.

2.5.2.3 Long-fiber reinforced composites. Long-fiber reinforced composites consist of a matrix reinforced by a dispersed phase in form of continuous fibers.

Unidirectional orientation of fibers.

Bidirectional orientation of fibers (woven).

2.5.2.4 Laminate Composites

When a fiber reinforced composite consists of several layers with different fiber orientations, it is called multilayer (angle-ply) composite.

2.6 FABRICATION METHODS AND ASSOCIATED PROBLEMS.

There are numerous fabrication methods that have been invented for specific composites. The processes of unification of these methods give rise to three broad methods: solid phase, powder and liquid phase methods. Several investigators have reviewed the synthesis of MMCs and, especially, AMCs. Traditional molten processing (MP) involves a variety of methods, including Mixing/Vortex, Infiltration and Rheocasting; some of these MP routes are currently being extended to a secondary processing stage such as extrusion. Methods other than the MP routes include P/M, Spray atomization/codeposition (SD) and in-situ production. The various fabrication methods include the following :(Ejiofor and Reddy, 1997)

1. Mixing/Vortex: in the mixing/vortex method, the pretreated and prepared filler phase is introduced in a continuously stirred molten matrix and then cast. The use of an inert atmosphere or vacuum other than air is essential to avoid the entrapment of gases. Mixing can be affected ultrasonically or by reciprocating rods, centrifuging or zero-gravity processing that utilizes an ultrahigh vacuum and high temperature for long periods of time. Difficulties such as the segregation/settling of secondary phases in the matrix, agglomeration of ceramic particulate, particulate fracture during agitation and extensive interfacial reactions are often encountered.
2. Infiltration: in this process, the molten metal penetrates a pretreated formed and prepared particulate bed or preforms with or without pressure. In the case of pressureless infiltration, the molten alloy infiltrates the reinforcement by percolation. This method is normally carried out in air, inert gas or evacuated atmosphere. Mortensen et al have associated this technique with such disadvantage as reinforcement-reinforcement contact, structural distortion of the preform, large grain size and undesirable interfacial reactions that culminate into microstructural inhomogeneity.

3. Rheocasting (compocasting): this permits the introduction of the pretreated particulate or short fibres into the solidifying, highly viscous and thixotropic dendritic slurry of the molten matrix by agitation. This mechanically entraps the ceramic reinforcements and prevents any form of segregation. Continued stirring then reduces the viscous mass to low-viscous, fine, nondendritic slurry. This results in a mutual interaction between the matrix melt and the filler phase which enhances wetting and bonding between the two phases. Pressure is usually used to effect a sound casting especially when the volume fraction (V_f) of the particulate material is greater than 0.3 or 0.5 in the case of short fibres. This is because the composite viscosities increase as V_f increases which is limiting at lower volume fractions. Fibre damage/degradation due to vigorous agitation is another difficulty. Owing to this effect, Rheocasting lends itself only to particulate composites with a very low V_f of low to medium density particulates. A fundamental characteristic of this technique is that the matrix alloy is isothermally held within the freezing range of the alloy and together with the reinforcement, is mechanically stirred. Stirring and agitation help to break the solid phases into smaller forms, releasing any particulate clusters that also break down in the process. New particle-matrix bonding can then take place through which particle agglomeration and gravity-induced settling is eliminated.
4. Powder Metallurgy (P/M): this is used in the synthesis of both AMCs and ceramic-matrix composites through the relatively low-cost methods of single compaction, double compaction and mechanical deformation following hot pressing as well as through high cost hydrostatic and isostatic compaction, hot dynamic compaction or explosive compaction methods. P/M involves the blending of well characterized matrix powders and discontinuous reinforcement compaction at ambient or hot conditions, degassing and consolidation. In these solid state techniques, sub-fusion temperature regimes are normally attained in consolidation for optimum results. Depending on the morphology of the reinforcement or the desirable properties, further processing by mechanical-deformation mechanisms is applied.

Liquid phase methods are good for fabricating various composite materials. It is however characterized by high reactivity of matrix/reinforcement system (Ray, 1993). 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 development of wide spectrum of fillers has allowed liquid phase technology to be applied to a wide range of systems (Abubakre and Khan, 2004) . The simplest of the liquid phase method is dispersion method; and stir casting is one of the dispersion methods. One of the advantages of using the stir casting method in Metal-Matrix Particulate composite (MMPC) production is the possibility of using conventional foundry equipment (Abubakre and Khan, 2004). Thus, standard stir casting equipment comprises the melting unit and the stirring mechanism. The melting equipment used are mostly the electrical resistance and induction heating furnaces and 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 1250rpm have been experimented by various researchers. An optimum stirring speed of 550rpm was suggested although with limitation. The fundamental basis for choice of speed is the ability to create vortex in the body of the Metal-Matrix (Abubakre and Khan, 2004). 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 (Surappa and Rohatgi, 1981).

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 (Abubakre and Khan, 2004). 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. 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, light weight, fuel conservation and improved efficiency (Abubakre and Khan, 2004).

2.7 Metal Matrix Composites (MMCs)

Traditional materials do not always provide the necessary properties under all service conditions. MMCs are advanced materials resulting from a combination of two or more materials (one of which is a metal and the other a non-metal) in which tailored properties are realized (Mahendra and Radhakrishna, 2007).

The need for new engineering materials with the advancement of modern technology in the areas of aerospace and automotive industries had led to a rapid development of Metal – Matrix composites. They can be tailored to have superior properties such as high specific strength and stiffness, increased wear resistance, enhanced high-temperature performance and better thermal and mechanical and creep resistance than those of monolithic materials. MMCs have an edge over polymer matrix composites because of their capability to withstand high temperatures, better transverse mechanical properties, superior thermal and electrical conductivities, excellent resistance to moisture, flame and radiation and zero out-gassing at vacuum.

Among the various matrix materials available, aluminium and its alloys are widely used in the fabrication of MMCs. This is because of the fact that they are light in weight, economically viable, amenable for production by various processing techniques and possess high strength and good corrosion resistance. Some of the important reinforcement materials are carbon/graphite, silicon carbide, alumina, zirconia and zircon in particulate, whisker or fibre form. Major fabrication methods used for aluminium MMCs are stir casting, Squeeze casting, Compocasting, Infiltration, Spray deposition, Direct melt oxidation process and Powder Metallurgy (Rajan et al, 1998).

Metal Matrix Composites (MMCs) are one of the four principal classes of man-made composites that can be distinguished by type of matrix. Two of these classes have ductile matrices: Metal Matrix Composites (MMCs) and Polymer-Matrix Composites (PMCs). Two have brittle matrices: Ceramic and Graphite/Carbon matrix composites (www.findarticles.com).

A MMC is a type of composite material with at least two constituent parts, one being a metal. The other material may be a different metal or another material such as a ceramic or an organic compound.

When at least three materials are present it is called a hybrid composite (wikipedia.org, 2006). MMCs are made by dispersing a reinforcing material into a metal matrix.

Some important commercial composites in each of these classes are described below (www.mrl.columbia.edu).

1. **Metal-Matrix Composites** : Metal-matrix composites (MMCS) are fabricated by plasma spray of the matrix material over properly laid fibers, liquid infiltration methods, physical vapor deposition, hot pressing, squeeze-casting, and other methods. MMCs have good high temperature capability, good transverse properties, and reasonably high compressive and shear strength, in part because of combination of good strength and toughness of the metal matrix and good interface-bonding. Common MMC systems include boron fibers in an aluminum matrix, SiC fibers or whiskers in an aluminum matrix, SiC in a titanium matrix, and carbon fibers in magnesium, copper, or aluminum matrices. Applications include piston heads for automotive engines, connecting rods in engine crankshafts, gas turbine blades, radar domes, and electronic packages.

2. **Polymer-Matrix Composites**: Polymer-matrix composites (PMCS) are the workhorse of the composites industry. They can have excellent room temperature properties at a low cost. They have been in use for about four decades. The matrix consists of various thermosetting resins and more recently, thermoplastic polymers reinforced by glass, carbon, boron, or organic fibers. The traditional application of PMCs was in secondary load-bearing aerospace structures. Now they are used in I beams in civil structures, various automotive parts, steel-belted tires, and in sports goods such as fishing poles, tennis rackets, golf clubs, and skis. The cost of these materials has been steadily decreasing, which makes them economical enough for use in consumer goods. Another interesting application of PMCs is in architectural structures such as the Georgia dome. The roof is composed of seven acres of woven glass fibers in a PTFE matrix.

3. **Ceramic-Matrix Composites**: Ceramic-matrix composites (CMCS) have been used in the form of reinforced concrete for a long time. Because of their low tensile strength, their use has been limited to structures subject to predominantly compressive loading. Ceramics are well known for their elevated

temperature oxidation and creep resistance. Therefore, if their brittle behavior could be controlled, these materials would be excellent candidates for use in automotive and aircraft gas turbine hot-section components such as blades, disks, pistons, and rotors.

The interface in these materials consists of mechanical bonding with some strength derived from inter diffusion between the fiber and the matrix. Cracking begins in the brittle matrix. When a crack tip encounters a fiber, two things can happen. If the fiber-matrix bond is strong, the crack will continue to grow across the fiber. In this instance, having fibers offers no apparent advantage. However, if the bond is weak, as in CMCS, delamination occurs at the interface, and the crack is temporarily stopped there with the energy going into the formation of new surfaces. When the load is raised further, the matrix on the other side of the fiber begins to crack but the fiber is still capable of transferring load across the crack faces. This phenomenon is called fiber bridging. When the fiber breaks, usually at a location away from the matrix crack plane because of continued fiber bridging. During subsequent loading, the fiber is pulled out of the matrix near the short end. This last step requires energy to overcome the frictional forces between the fiber and the matrix and raises the toughness level of CMCS. CMCs represent a relatively new class of materials that have caused considerable excitement in the composite and ceramic industries.

4**. Carbon-Carbon Composites:** As the name implies, in this class of fiber-reinforced composites both the matrix and the fibers are fabricated from carbon. These materials offer a unique combination of properties, including the ability to withstand extremely high service temperatures (>3000^{o}C), high specific strength, excellent resistance to wear (they can be self-lubricating), good resistance to thermal shock, and reasonable machinability. However, the maximum use temperature for these composites is limited by oxidation problems. Typical applications include brake components, heat shields, and rocket nozzles. Carbon-carbon composites can be fabricated using the CVD methods by impregnating graphite fibers with a carbon-based polymer that is then pyrolyzed to "burn off" the noncarbon atoms in the polymer, or combinations of the two.

2.8 Important MMCs (www.composite-by-design.com, 2007)

-Aluminium matrix:

- Continuous fibres: boron, silicon carbide, alumina, graphite
- Discontinuous fibres: alumina, alumina-silica
- Whiskers: silicon carbide
- Particulates: silicon carbide, boron carbide.

-Magnesium matrix:

- Continuum fibres: graphite, alumina
- Whiskers: silicon carbide
- Particulates: silicon carbide, boron carbide.

-Copper matrix:

- Continuous fibres, graphite, silicon carbide.
- Wires: niobium-titanium, niobium tin,
- Particulate: silicon carbide, boron carbide, titanium carbide.

2.9 MATRIX

The matrix is the monolithic material into which the reinforcement is embedded and is completely continuous – which means that there is a path through the matrix to any point in the material unlike two materials sandwiched together. In structural applications, the matrix is usually a lighter metal such as

aluminium, magnesium or titanium and provides a compliant support for the reinforcement. In high temperature applications, cobalt and cobalt-nickel alloy materials are common (wikipedia.org, 2006).

2.10 REINFORCEMENT

The reinforcement material is embedded into the matrix. The reinforcement does not always serve a purely structural task (reinforcing the compound) but is also used to change physical properties such as wear resistance, friction coefficient or thermal conductivity. The reinforcement can even be continuous or discontinuous (wikipedia.org, 2006). Continuous reinforcement uses monofilament wires or fibres such as carbon fibre or silica carbide. Because the fibres are embedded into the matrix in a certain direction, the result is an anisotropic structure in which the alignment of the material affects its strength. Discontinuous reinforcement uses "whiskers", short fibres or particles (wikipedia.org, 2006).

Particulate reinforced metal matrix composites which exhibit distinctive properties of high stiffness, high strength, good wear resistance and low coefficient of thermal expansion that could not be found in monolithic materials have promoted an increasing number of applications in many areas. Recent studies have found that ceramic particle such as SiC and Al_2O_3 can act as load bearing component and improve the wear resistance of composites. However, these ceramic reinforcements also result in high-friction coefficient and wear rate of the counterpart. Graphite was found to decrease the coefficient of friction and wear rates of the materials effectively when it was added into the metal matrix (Zhan et al, 2004).

2.11 Manufacturing and forming methods (wikipedia.org, 2006)

MMC manufacturing can be broken into two types: solid and liquid.

Powder blending and consolidation (powder metallurgy processing), diffusion bonding and vapour deposition techniques come under the solid state processing. The liquid state processes include stir casting, spray deposition, squeeze casting, infiltration and in- situ (reactive) processing.

MMCs are nearly always more expensive than the more conventional materials they are replacing. As a result, they are found where improved properties and performance can jointly added cost. These application

are found today most often in aircraft components, space systems and high-end or "boutiques" sports equipments.[9]

In comparison with conventional polymer matrix composition, MMCs are resistant to fire, can operate in wider range of temperatures, do not absorb moisture, have better electrical and thermal conductivities, are resistant to radiation.

2.12 Aluminium Matrix Composites (AMCs)

Aluminium alloys encompass a wide range of chemical compositions and product forms that can be manufactured by all available metal working techniques and standard casting processes. Manufactured forms of aluminium and aluminium alloys include standard mill products (e.g. sheet, plate, foil, rod, bar, wire, tube, pipe and structural forms) and engineering forms for specific applications produced by extrusion, forging, stamping, powder metallurgy, semisolid processing and machining. Aluminium products also include metal matrix composites with either particulate or fibre reinforcement (Warmuzek, ASM 2004)

Aluminium matrix composite, like all composite are not a single material but a family of materials whose stiffness, strength, density, thermal and electrical properties can be tailored. The matrix alloy, the reinforced material, the volume and shape of the reinforcement, the location of the reinforcement and the fabrication method can all be varied to achieve required property. Regardless of the variation however, aluminium composite offer the advantage of low cost over most other MMCs.

Aluminium MMCs are produced by casting, powder metallurgy, in-situ development of reinforcements and foil-and-fibre pressing techniques. They are applied in brake rotors, pistons and other automotive components as well as golf clubs, bicycles, machinery components, electric substrate, extruded angles and channels and a wide variety of other structural and electronic applications (www.composite-by-design.com, 2007).

Aluminium alloy particle reinforced composites have formed a wide range of applications in automobile, aerospace and other engineering applications. These are due to the fact that these composite

materials offer excellent combinations of physical, mechanical and tribological properties. Furthermore there is enough flexibility in design to tailor the materials for specific applications and for specific property requirement (Rajput et al, 2007).

For applications in the automotive, transportation, construction and leisure industries, affordable cost is also an essential factor.

2.13 Aluminium-graphite composites

Composite materials offer many improvements over the base materials. Properties such as bearing, lubricating, damping and machinability can be appreciably enhanced. Aluminium and its alloys are extensively used in a large number of industrial applications due to their excellent combination of properties e.g. high strength-to-weight ratio, good corrosion resistance, better thermal conductivity and easy to deform. Due to high strength-to-weight ratio, automobile and aircraft components are generally manufactured out of aluminium alloys in other to make the moving vehicles lighter which results in saving in fuel consumption. However, the use of aluminium alloys as an antifriction material has been limited because of unfavorable wear. They tend to seize when run under boundary lubrication condition (www.freepatentsonline.com, 2007). When two solid surfaces are brought in close proximity they are attracted to each other due to interactions between the surface atoms. If the surfaces are clean, perfect and are of the same chemical composition, they tend to weld to each other under slight pressure since chemical bonding is established between the atoms on the two surfaces. This phenomenon manifests itself as seizure of sliding metal contacts. Aluminium alloys are especially notorious for their tendency to seize when mated under sliding contacts. The problem of aluminum seizing against aluminium is particularly severe under boundary lubrication conditions when there is essentially no oil supply between the mating members. However, even under conditions of fluid film lubrication, aluminium alloys seize due to instabilities in the system which causes localized breakdown of the oil film and leads to direct contacts between the mating

members. The seizure resistance of an alloy is greater if it can withstand inadequate lubrication without seizure (Rohatgi and Pai, 1974).

To improve the wear resistance, it has been proposed to disperse graphite particles in aluminium materials. This will not only improve the wear resistance, but will also ameliorate damping capacity and machinability of the base alloy (www.freepatentsonline.com, 2007). Aluminium alloys dispersed with solid lubricant particles such as graphite have been established as potential engineering materials for a number of antifriction applications. The role of graphite in such applications is to reduce the friction and wear of materials by forming a tribo-induced layer of graphite on the mating surfaces, thereby reducing direct metal – to – metal contact (Prasad and Das, 1991). In recent years considerable attention has been given to the preparation and study of the properties of cast aluminium alloy-graphite particle composites (Krishnan et al, 1981). Graphite is a solid lubricant and its presence in aluminum alloy matrices makes the alloys self-lubricating (www.freepatentsonline.com, 2007). Self lubricating materials offer many improvements over the materials to which lubricant needs to be applied periodically. Among these materials, considerable work has been done on aluminium alloy-graphite particulate composites (Al/GrpCs). It has been shown that these light weight MMCs exhibit low friction and wear, reduced temperature rise at the wearing contact surface, excellent anti-seizure effects, improved machinability, low thermal expansion and high damping capacity. These characteristics have made the Al/Gr system a potential candidate for automotive and general engineering applications (Akhlaghi and Pelaseyyed, 2004).

A solid state lubricating film could be formed on the wearing surface after adding graphite particulate into Al-alloy. It helps to reduce friction coefficient, contact temperatures and abrasive wear of the lubricating surface. It also helps to increase the anti-seizing effect and tribological behavior of Al-alloy. Under insufficient liquid lubrication, the solid state lubricating film of graphite can be used as a remedy (Lin et al, 1988).

During the sliding of aluminium alloy dispersed with graphite particulates, a layer of graphite is usually present at the sliding surface. This tribo-layer significantly reduces the amount of direct metal-to-

metal contact giving rise to low friction and a low rate of wear, making these composites useful candidate materials for anti-friction applications (Lim et al, 1997).

Engine system has about 41% energy loss due to wear of the parts. Engine cylinders made from Al alloy/graphite particulate composite exhibit higher seizure resistance and a lower frictional coefficient and wear rate compared with ceramic owing to the lubricating effect of graphite (yang et al, 2004).

The properties of aluminium/graphite particulate composites have been studied extensively. In these composites, graphite is presumed to improve tribological properties by forming graphite-rich lubricant film between the sliding surfaces (Yang et al, 2004). According to Prasad and Rohatgi (1987), the formation of a graphite lubricant film depends on the nature of the sliding surfaces, the test condition and the environment. Liu et al (1993) has shown that the aluminium alloys containing graphite particulate, the graphite- rich lubricating film offers lower friction coefficient, wear rate and friction temperature. The seizure of aluminium is known to occur very readily when subjected to sliding contact (Yang et al, 2004). According to Rohatgi and Pai (1974), the seizure resistance and wear rate of aluminium alloy can be improved by adding graphite particulates into the aluminium alloy.

In recent years, considerable attention has been given to the preparation and study of the properties of cast aluminium alloy – graphite composites. Aluminium alloy – graphite particulate composites are excellent bearing materials and it has been reported that they compare well with many copper alloys including brasses and bronzes. Pistons and cylinder liners made using aluminium alloys containing dispersed graphite particles have been successfully used in internal combustion engines (Krishnan et al, 1981)

Aluminium and aluminium alloys such as Aluminium-Silicon (Eutectic, Hypo and Hyper), Aluminium-Copper, Aluminium-Silicon-Copper, Aluminium-Magnesium, Aluminum-Silicon-Magnesium, and Aluminum-Silicon-Magnesium-Copper form the base material for the composites (www.freepatentsonline.com, 2007).

The most significant advantage of graphitic-aluminium is reduction in weight to one-third as compared to cast iron and copper base alloys. This reduces the weight and consequently the fuel consumption of vehicle.

Dispersed graphite particles in aluminium matrices act as a solid lubricant and improve tribological properties. Components made out of graphic-aluminium would be cheaper i.e. costing one-third of copper base alloys. Aluminium alloy-graphite particle composites can successfully be used for pistons, cylinder blocks, bearing etc. Resistance to seizure of the composite is very good. It can be run under boundary lubrication without seizing. Temperature rise in the bearing is reduced by the addition of graphite particles. Graphite acts as a solid lubricant and reduces wear losses during friction (www.freepatentsonline.com, 2007).

CHAPTER THREE

EXPERIMENTAL PROCEDURE

3.0 MATERIALS

High purity aluminium and copper electrical wires obtained from Northern Cable Company (NOCACO), Kaduna, graphite particulate which was sieved to a particle size of 125µm was obtained from NMDC, Jos, moulding boxes, magnesium powder obtained from a chemical shop in Zaria, acid etch ants (5ml HNO_3, 2ml HF and 100ml distilled water), polishing cloth and polishing powder were used for the research.

3.1 EQUIPMENT

The equipment used include manual stirrer, graphite crucibles, electrical resistance furnace, Hounsfield Balanced impact machine (Serial no. 3203) from Mechanical Engineering Department A.B.U. Zaria. Others are Rockwell hardness tester from Metallurgical and Materials Engineering Department, A.B.U. Zaria, Insron Electro-mechanical Testing System (model 3369) from Centre for Energy Research and

Development (CERD) O.A.U., Ile-Ife, grinding and polishing machines and metallurgical microscope with in-built camera which is connected to a computer system (model NJF- 120A)all from the Metallurgical and Materials Engineering Department, A.B.U. Zaria .

3.2 METHODOLOGY

The AMCs used in this research was produced using the stir-casting method at the Foundry shop of Uhuotu Engineering Company, Jos, Nigeria. The specimen was produced by keeping the percentage of copper constant at 5% and varying the graphite particulate in the range 1, 3, 5, 7 and 9%, while the control sample was without graphite particulate. The melting was carried out in graphite crucible in a resistance furnace. Al- 5% Cu alloy was produced before melting it again so as to add the graphite particulates. The graphite particulate was bought from a chemical shop in Jos and then it was sieved to 125μm size for use as reinforcement.

Weighed amount of graphite particle was placed in the crucible and covered with a lid. As soon as the melting crucible was heated up, weighed amount of the aluminium alloy was charged and the crucible was covered. The surface of the alloy was covered using a fluxing agent when it reached a semi-pasty stage. At about 700^0C, the cover flux was worked into the metal. A reactive metal (magnesium) of about 1% by weight of the melt was gradually introduced into the melt with the help of a tong to improve wettability. A proper mixing was carried out after which the mixture was agitated and the slag removed. At this stage, the melt was ready for the introduction of activated graphite and the temperature was maintained at about 700^0C – 720^0C. The graphite particulates was heated up in the small crucible to a temperature of about 400^0C and held for 2 hours and it was agitated now and then to achieve uniform heating and to remove volatile matters from the powder.

The melt was continually being stirred to give rotary motion. At this stage, the activated graphite particulate was then added. The addition being slow and stirring continuing until the entire graphite particle has been added.

After the complete addition of the graphite particulates, stirring was continued for a minute at a lower rate. The stirrer was then stopped and removed and the whole melt was allowed for $2 - 2^1/_2$ minutes and then cast bars with diameter 20mm and 350mm length were prepared and subsequently the melt was poured in the bars.

After casting, the density and porosity of the varying composition produced were determined and the specimens were machined into tensile, impact and hardness test specimens for the purpose of determining the mechanical properties. Heat treatment was also carried out and the mechanical properties were also determined.

3.2.1 Determination of Density

The basic method of determining the density of a sample by measuring the mass and volume of the sample was used. The density of the sample was estimated using the formula given below:

$$\text{Density} = \frac{\text{mass}}{\text{Volume}} \text{ g/cm}^3 \quad \ldots\ldots (1)$$

3.2.2 Determination of Apparent Porosity

The samples were kept in the oven at 110°C for 3 hours to obtain constant weight D. The sample was then suspended in distilled water and boiled on a hot plate for 30 minutes. After boiling, while still in hot water, the water is displaced with cold water and the weight S was determined on a balance hinged on a tripod stand. The test sample was removed from the water and extra water wiped off from the surface by lightly blotting the sample with wet towel and the weight W of the soaked sample suspended in air was measured. The apparent porosity of the sample was determined using the relationship below:

$$P_a = \frac{W-D}{W-S} \times 100\% \quad \ldots\ldots (2)$$

P_a = apparent porosity.

3.2.3 Heat Treatment of the Samples

The test samples were solution heat-treated at temperature of 520^0C in an electrical heat-treatment furnace and held for 2 hours at this temperature and then rapidly quenched in warm water (50^oC). After which ageing of the test samples were carried out at temperatures of 100^0C, 200^0C and 300^0C for various ageing time intervals of 60 minutes for 360minutes and then cooled in air. The hardness values of each composition were taken to assess the peak ageing time for the various ageing temperature employed.

3.3 MECHANICAL PROPERTIES

The following mechanical tests were carried out to asses the effects of the graphite particulate in the Al-5%Cu matrix composite.

3.3.1 Tensile Test

The cast bars were machined into standard tensile specimens with diameter 9mm and gauge length of 30mm to get the tensile properties of the composite material for each composition and for both the as-cast and heat treated conditions using the Insron Electro-mechanical Testing System(model 3369**)**.

3.3.2 Hardness

The hardness values were determined for both the as-cast and heat treated samples using the Rockwell hardness test machine on B scale. The machine used was the universal hardness test machine (8187.5 LKV model B). The indenter used was a 1.58mm steel ball with a minor load of 10kg and a major load of 100kg

3.3.3 Impact Strength

The impact strength of the samples was investigated using the Hounsfield Balanced impact machine (Serial no. 3203) for the as-cast and heat treated conditions.

3.3.4 Microstructure

The samples were subjected to metallographic analysis for both the as-cast and heat-treated samples so as to record the microstructures of various composition obtained by the use of metallurgical microscope (model NJF-120A) which is connected to a computer system.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION

4.1 RESULTS

The results for the density and apparent porosity for various addition of graphite particulate are shown in figures4.1 and 4.2 respectively and tables 1 and 2 respectively (Appendix).

The various ageing times with temperature on different additions of the graphite particulate are shown in figures 4.3 to 4.5 and Tables 3-5 (Appendix) while the results of the mechanical properties with various additions of the reinforcement are shown in figures 4.6 to 4.11 and Tables 6-11 (Appendix).

The various microstructures obtained for different additions of the graphite particulate are shown in Plates I-XXIV.

4.1.1 Microstructural Analysis

The various microstructures of the Al-5%Cu alloy with different weight percent graphite particles are as shown in Plates I-XXIV. The microstructures of the as-cast and heat-treated composites at various ageing temperatures and peak aged times were examined by the use of metallurgical microscope which is connected to a computer system model NJF-120A. They were observed to contain essentially the α-Al, Al-Cu ($CuAl_2$), intermetallic compounds as well as the graphite particles which mostly exist at the grain boundaries due to segregation and consequent rejection of impurities during segregation as captured in Plates I-XXIV.

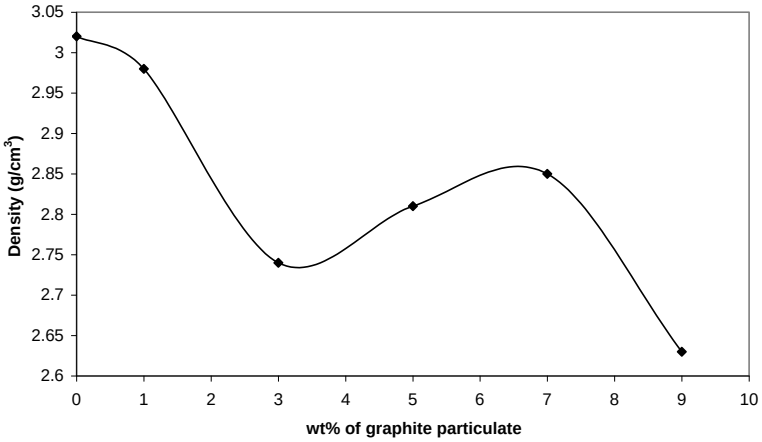


Figure 4.1: Variation of density with weight % addition of graphite particulate

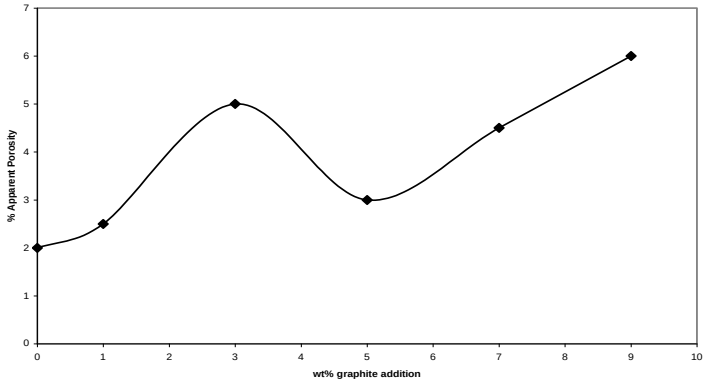


figure 4.2: Variation of percentage porosity with wt% of graphite addition

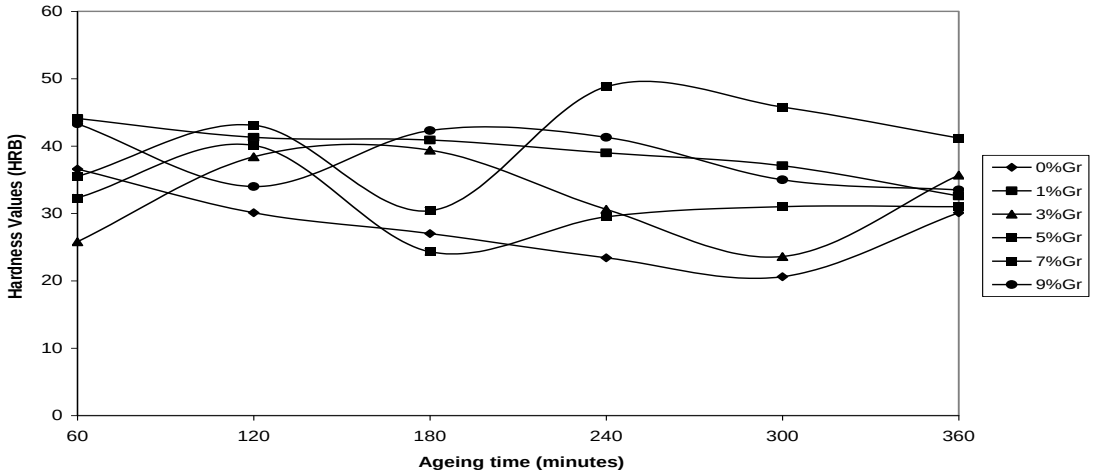


Figure 4.3: Variation of hardness values with additions of graphite particulate at ageing temperature of 100°C

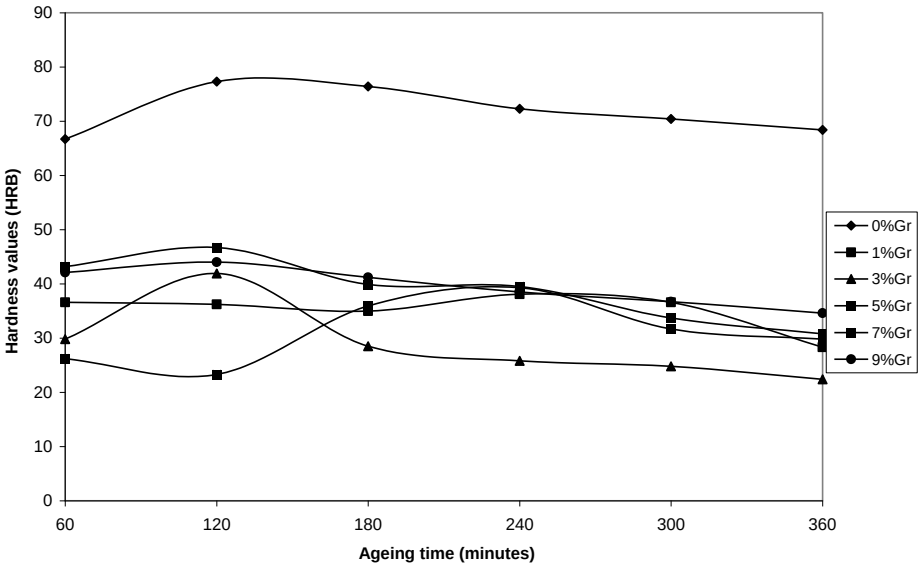


Figure 4.4: Variation of hardness values with addition of graphite particulate at ageing temperature of 200°C

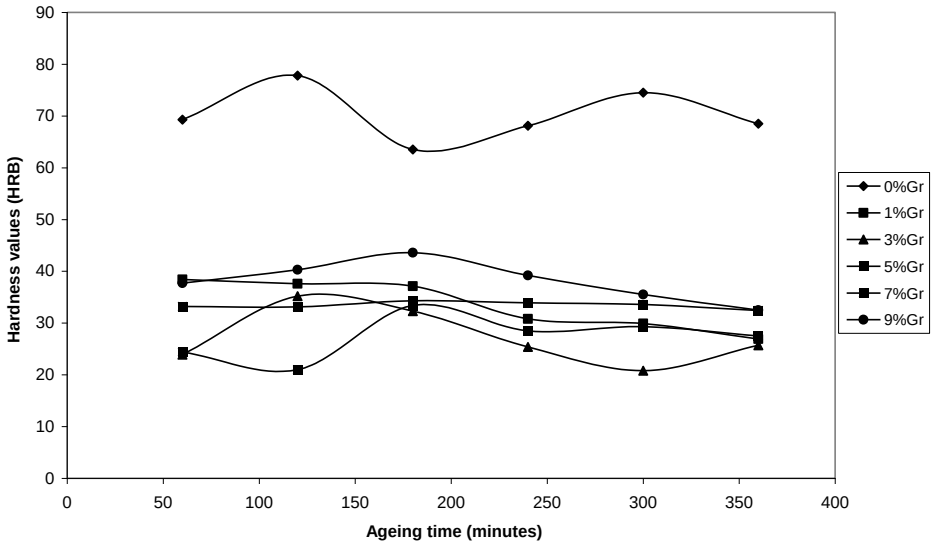


Figure 4.5:Variation of hardness values with addition of graphite particulate at ageing temperature of 300^{o}C

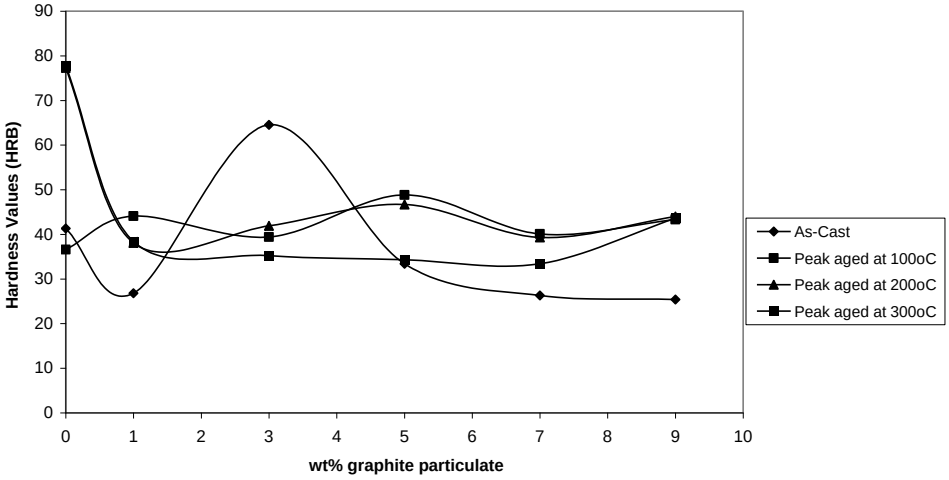


Figure 4.6: Variation of Hardness Values with addition of graphite particulate

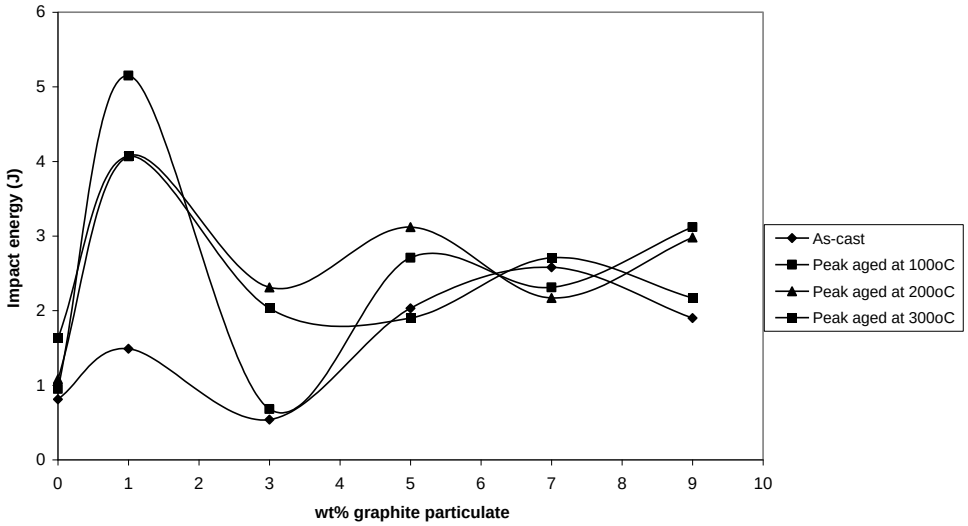


Figure 4.7: Variation of Impact energy with addition of graphite particulate

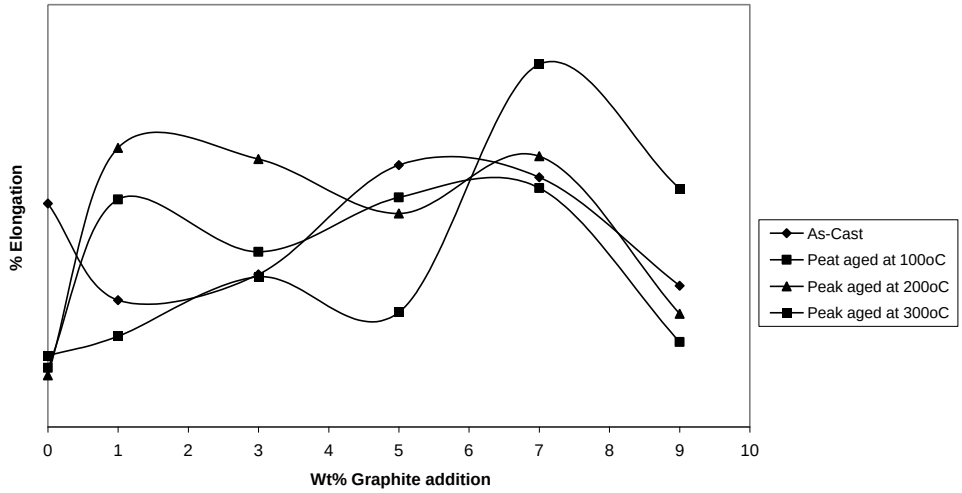


Figure 4.8:Variation of percent elongation with wt% of Graphite additions

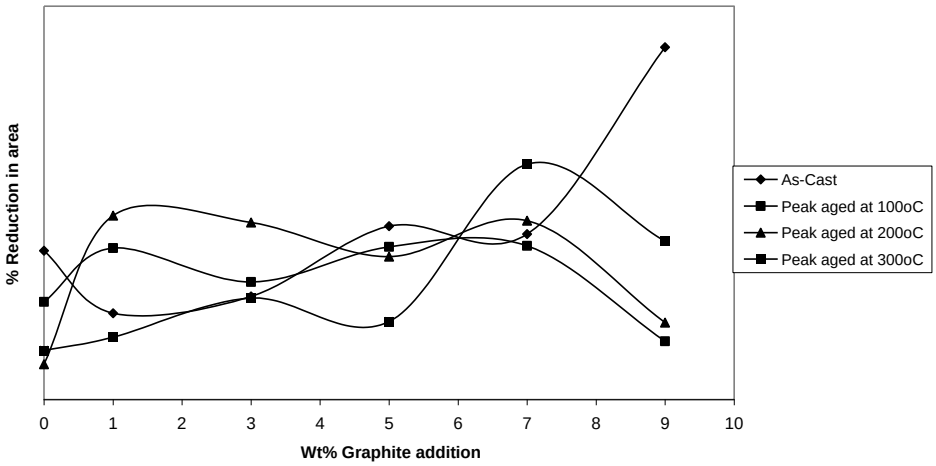


Figure 4.9:Variation of percent reduction in area with Wt% of Graphite additions

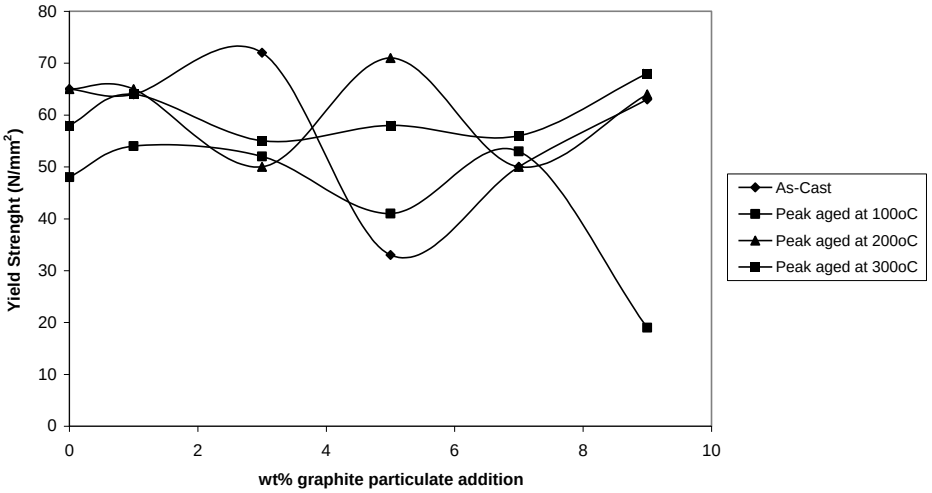


Figure 4.10 Variation of Yield Strenght with weight fraction of graphite particulate addition

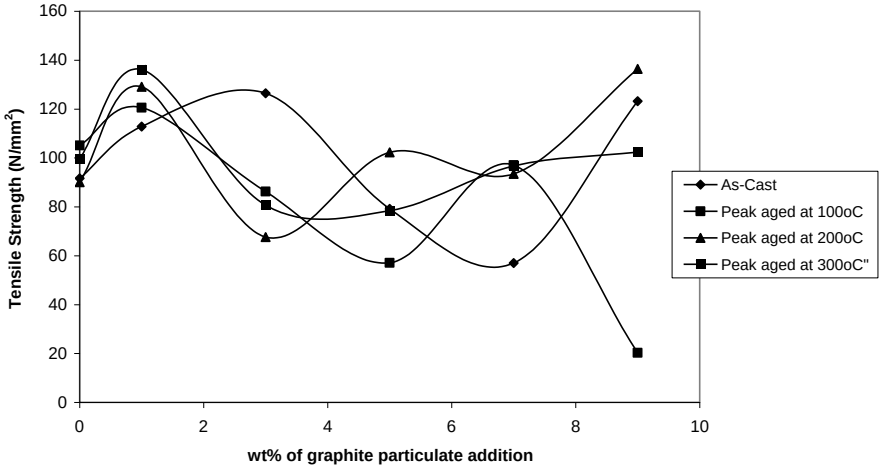


Figure 4.11: Variation of Tensile Strenght with weight fraction of graphite particulate additions

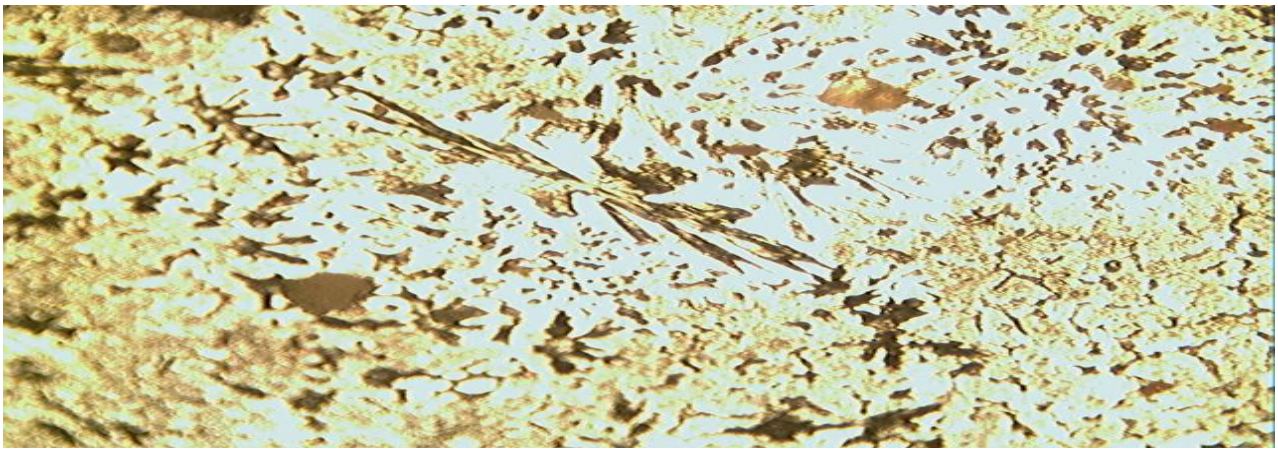


Plate I: Microstructure of Al-5%Cu showing globules and plates of Al-Mg compound and a network of $CuAl_2$ compound (dark) in the matrix of Al (white). (X200) etchant: acid etchant

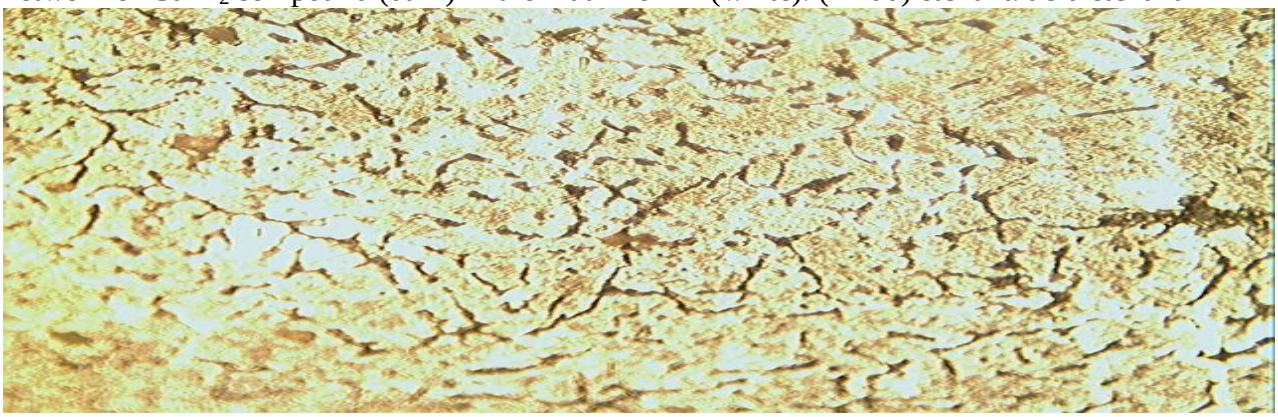


Plate II: Microstructure of Al-5%Cu reinforced alloy with 1wt%Gr showing a network of compounds and $CuAl_2$ and graphite particulates mainly at the grain boundaries in the Al-matrix (white). (x200) etchant: acid etchant

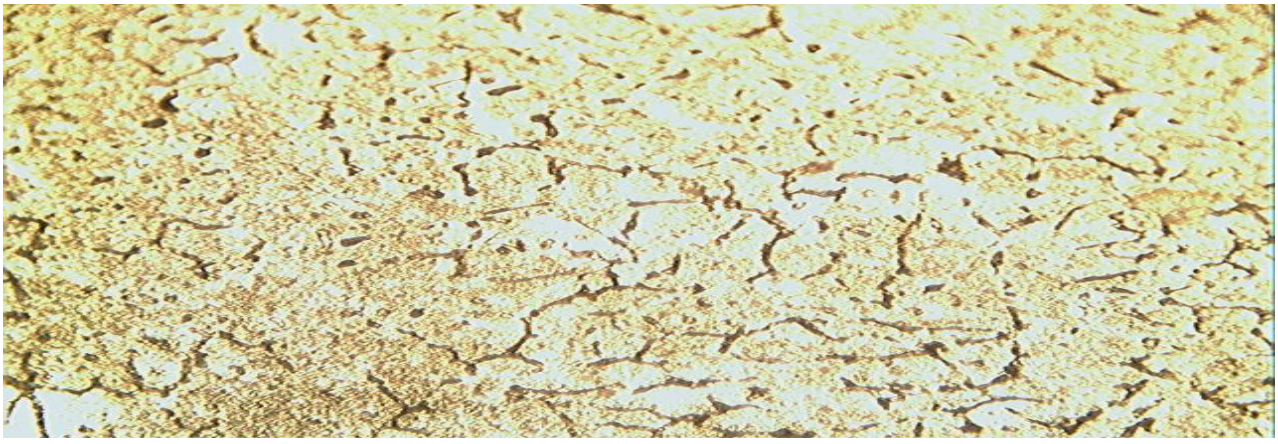


Plate III: Microstructure of Al-5%Cu alloy reinforced with 3wt%Gr showing network of Al-Cu and other compounds (dark) with distribution of graphite particles in the grain boundaries in the Al-matrix. (200) etchant: acid etchant

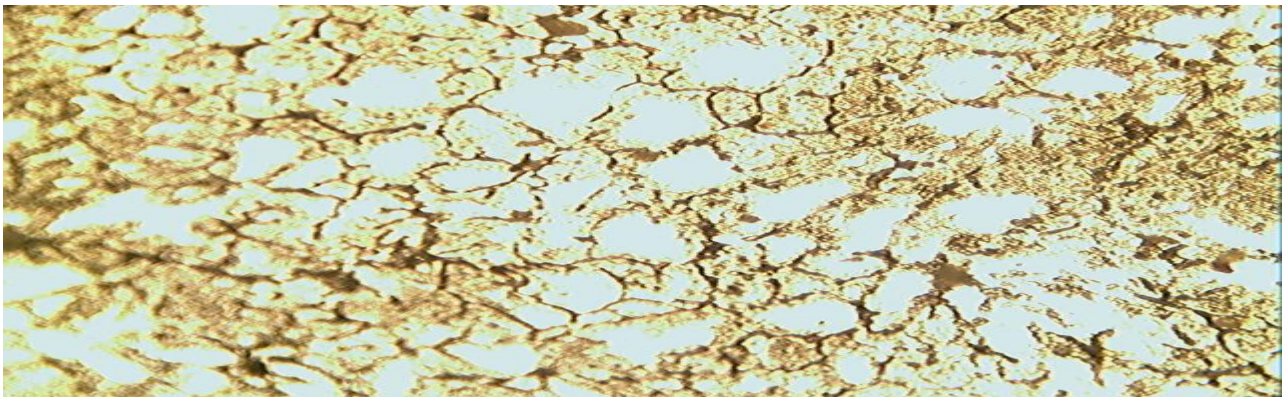


Plate IV: Microstructure of Al-5%Cu alloy reinforced with 5wt%Gr showing network of Al-Cu and other compounds (dark) with graphite distribution in the grain boundaries in the Al-matrix (white) (X200) etchant : acid etchant

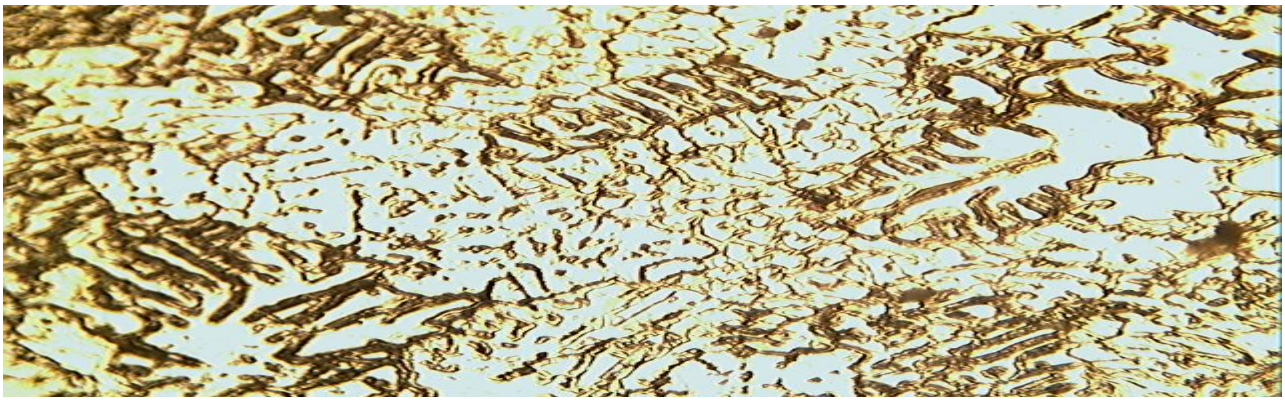


Plate V: Microstructure of Al-5%Cu alloy reinforced with 7wt%Gr showing massive distribution of the graphite particulates in the matrix and grain boundaries in addition to the Al-Cu and other compounds in the al-matrix. Also the structure is dendritic. (X200) etchant: acid etchant

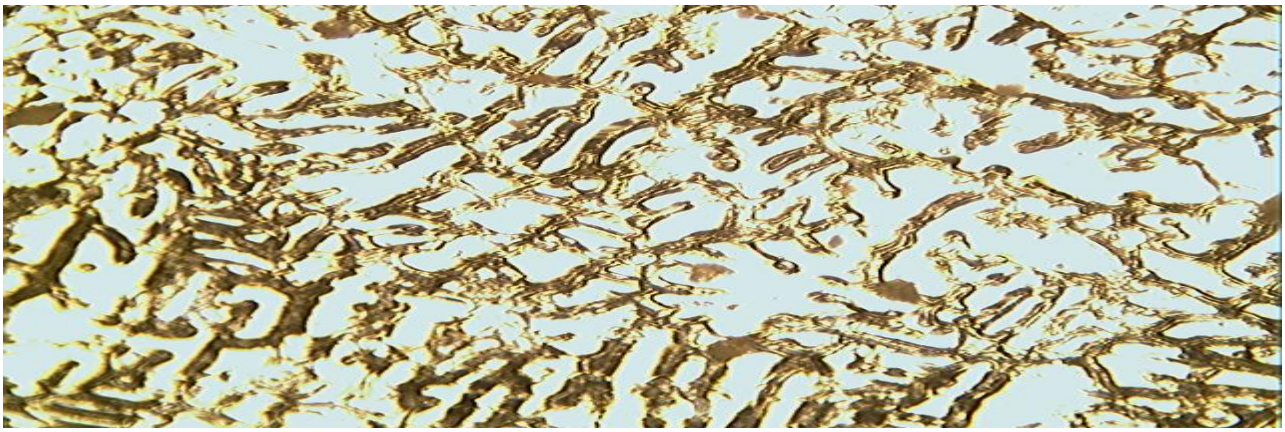


Plate VI: Microstructure of Al-5%Cu alloy reinforced with 9wt%Gr showing dendrites with little spacing between the arms and distribution of graphite particles as well as the $CuAl_2$ and other compounds in the grain boundaries (dark) in the Al-matrix (white). (X200) etchant: acid etchant

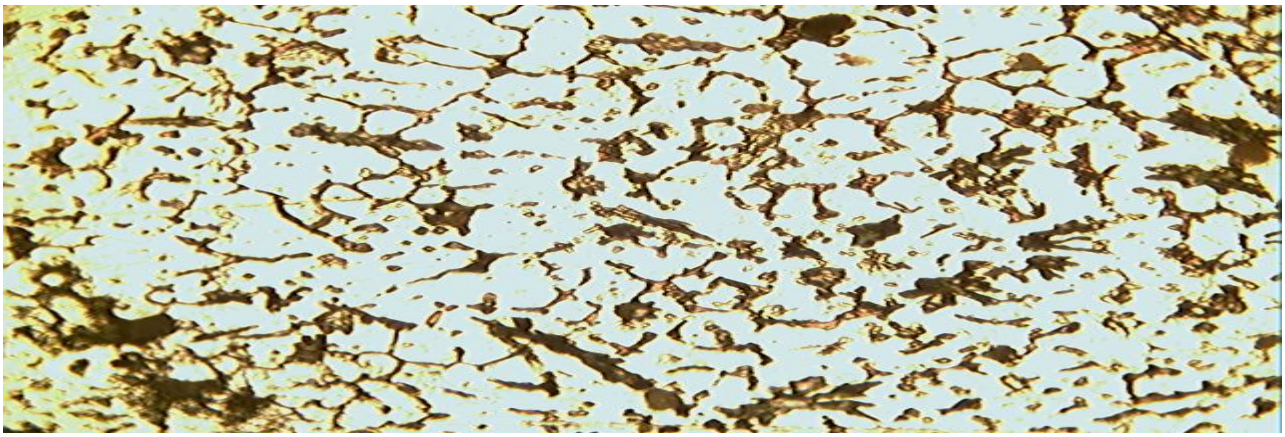


Plate VII: Microstructure of Al-5%Cu peak aged at 100^{o}C showing interdendritic network of both $CuAl_2$ and other compounds (dark) in the matrix of Al (white) (X200). Etchant: acid etchant

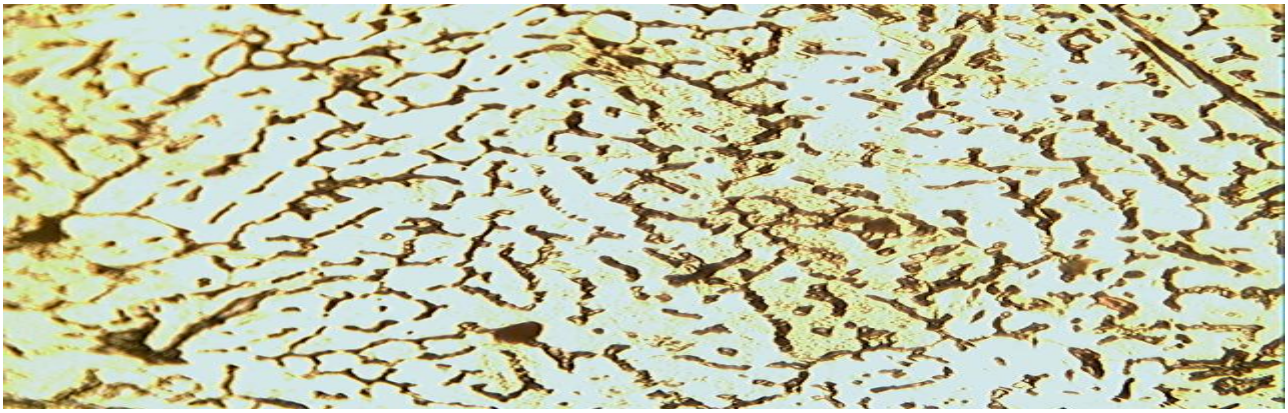


Plate VIII: Microstructure of Al-5%Cu peak aged at 200^{o}C showing a network of $CuAl_2$ and other compounds (dark) in the matrix of Al (white). (X200) etchant: acid etchant



Plate IX: Microstructure of Al-5%Cu peak aged at 300^{o}C showing more pronounced plates of Al-Mg compound together with the Al-Cu compound (dark) in the Al-matrix (white) (X200). Etchant: acid etchant

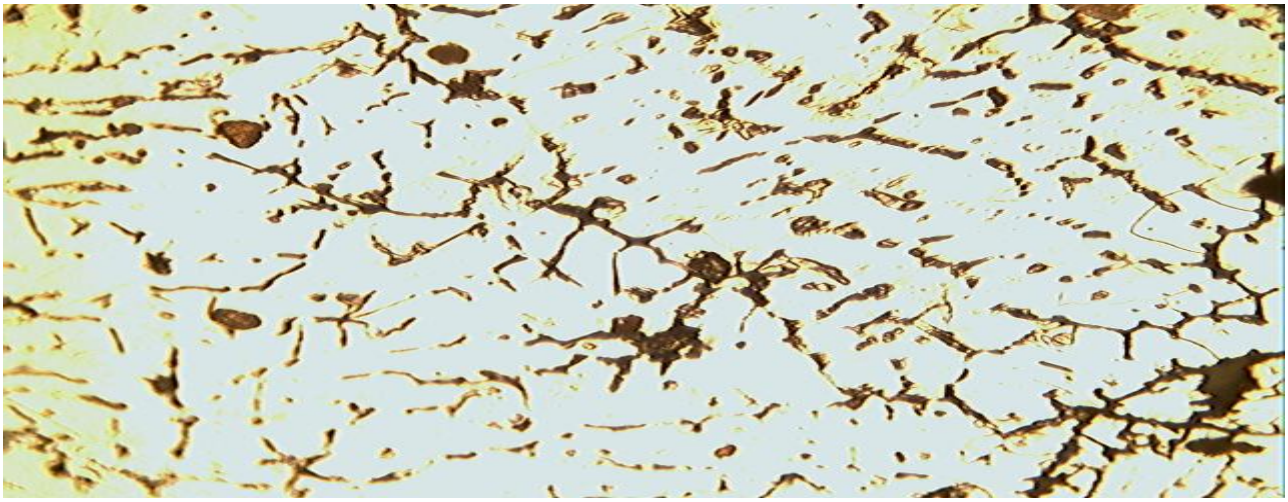


Plate X: Microstructure of Al-5%Cu reinforced with 1wt%Gr peak aged at 100^{o}C showing a network of compounds including the graphite particles at the grain boundaries (dark) in the Al-matrix (white) (X200). Etchant: acid etchant

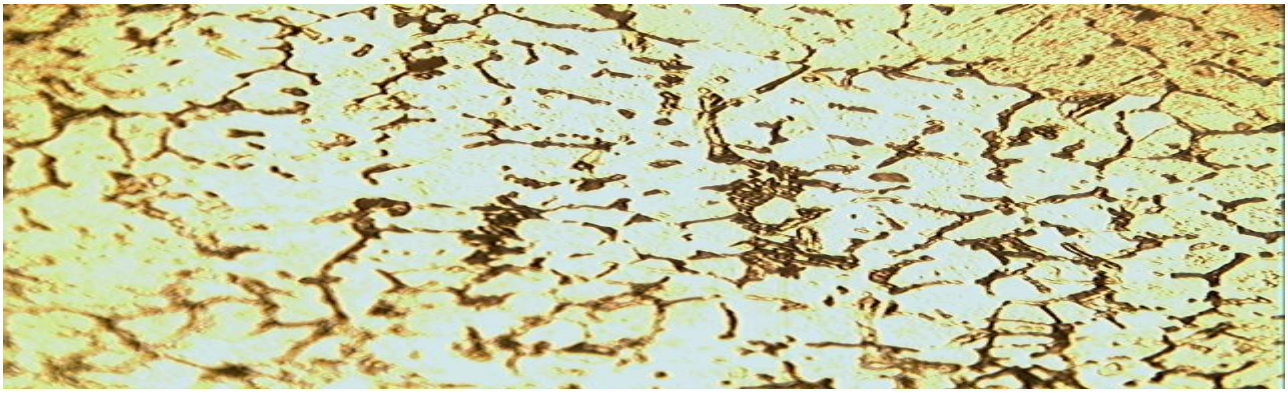


Plate XI: Microstructure of Al-5%Cu reinforced with 1wt%Gr peak aged at 200^{o}C showing a network of compounds including the graphite particles in the grain boundaries and also within the matrix in the Al-matrix (white) (X200).etchant: acid etchant

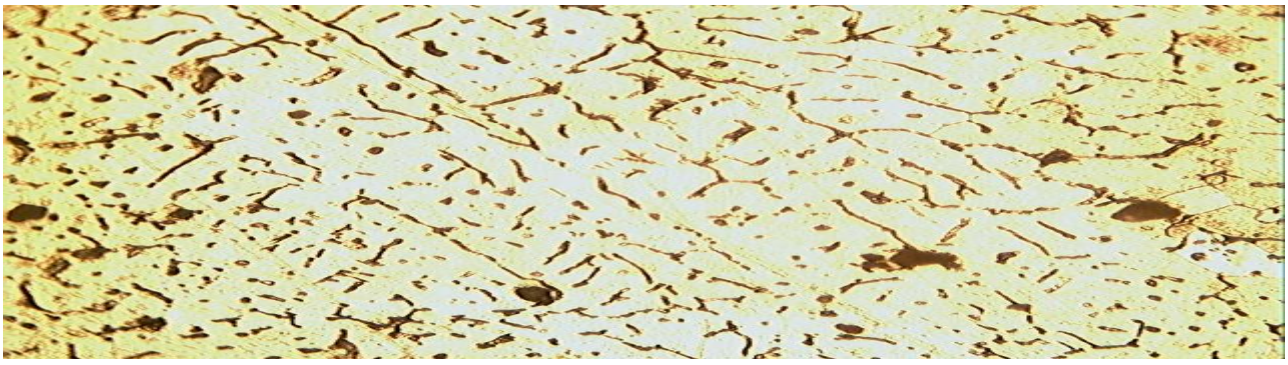


Plate XII: Microstructure of Al-5%Cu reinforced with 1wt%Gr peak aged at 300^{o}C showing distribution of Al-Cu and other compounds mostly at the grain boundaries (dark) in the Al-matrix (white) (X200). Etchant: acid etchant

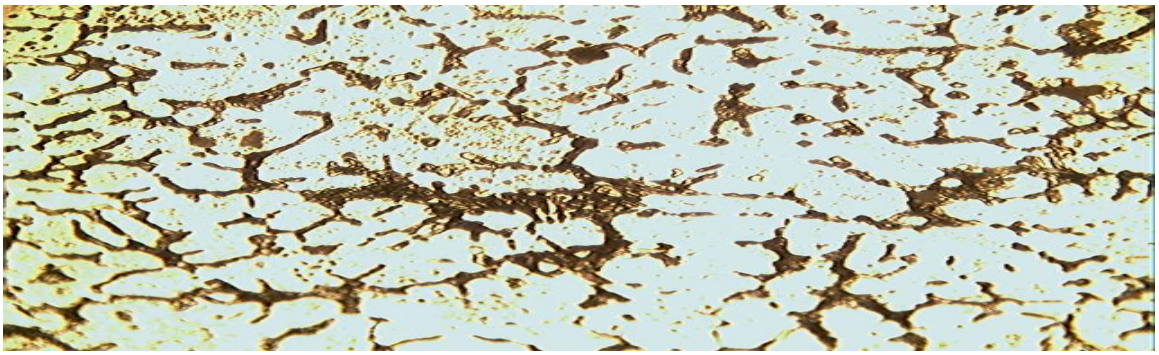


Plate XIII: Microstructure of Al-5%Cu reinforced with 3wt%Gr peak aged at 100^{o}C showing massive $CuAl_2$and other compounds (dark) with a distribution of graphite particles in the grain boundaries in the Al-matrix (white). (X200) etchant: acid etchant

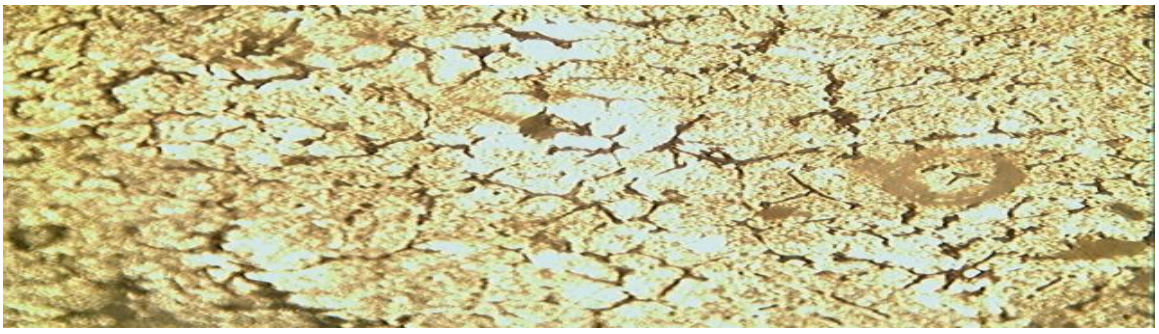


Plate XIV: Microstructure of Al-5%Cu reinforced with 3wt%Gr peak aged at 200^{o}C showing network of $CuAl_2$ and other compounds (dark) with graphite particulate in the grain boundaries in the Al-matrix (white) (X200). Etchant: acid etchant

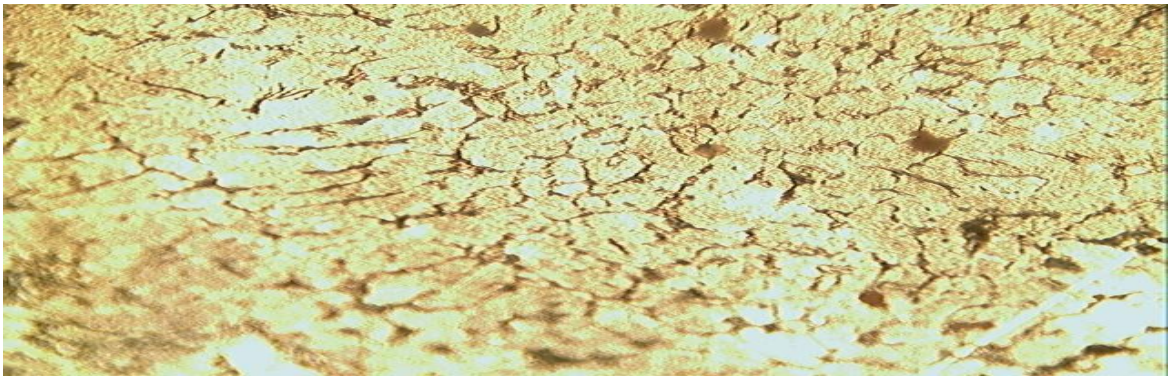


Plate XV: Microstructure of Al-5%Cu reinforced with 3wt%Gr peak aged at 300^{o}C showing structures of $CuAl_2$ precipitates and other compounds (dark) with distribution of graphite particles in the grain boundaries in the Al-matrix (white) (X200) etchant : acid etchant

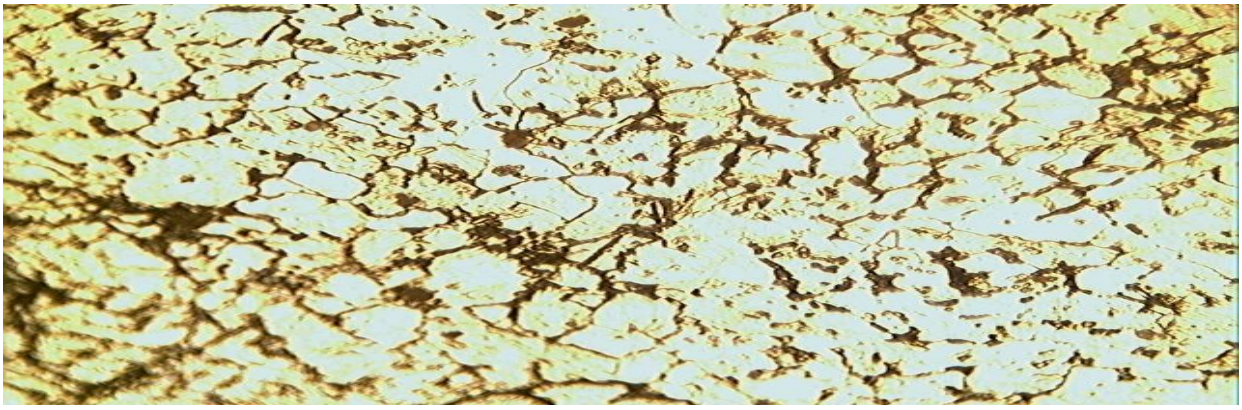


Plate XVI: Microstructure of Al-5%Cu reinforced with 5wt%Gr peak aged at 100^{o}C showing a network of $CuAl_2$precipitates and other compounds (dark) with distribution of graphite particles mostly at the grain boundaries in the Al-matrix (white) (X200). Etchant: acid etchant

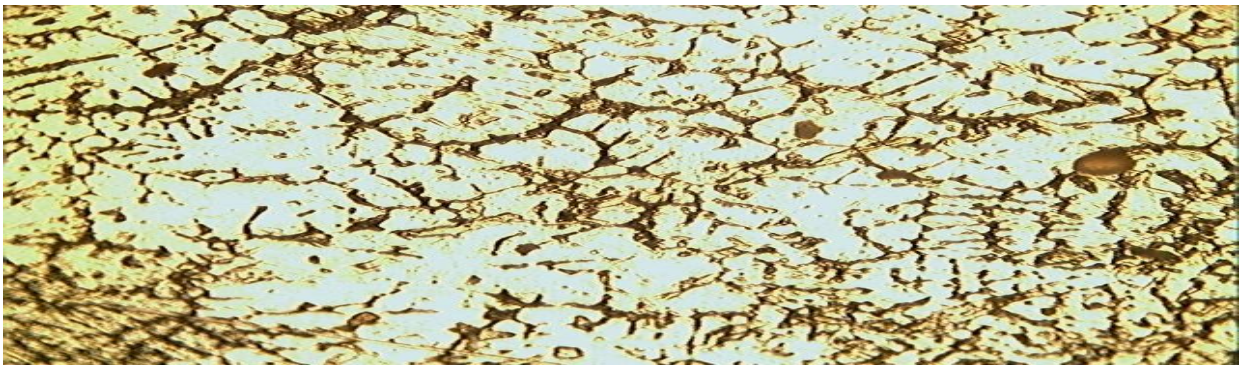


Plate XVII: Microstructure of Al-5%Cu reinforced with 5wt%Gr peak aged at 200^{o}C showing network of precipitates of $CuAl_2$ and other compounds with a dendrite like structure (dark) with heavy distribution of graphite particles at the grain boundaries in the al-matrix (white) (X200) etchant : acid etchant

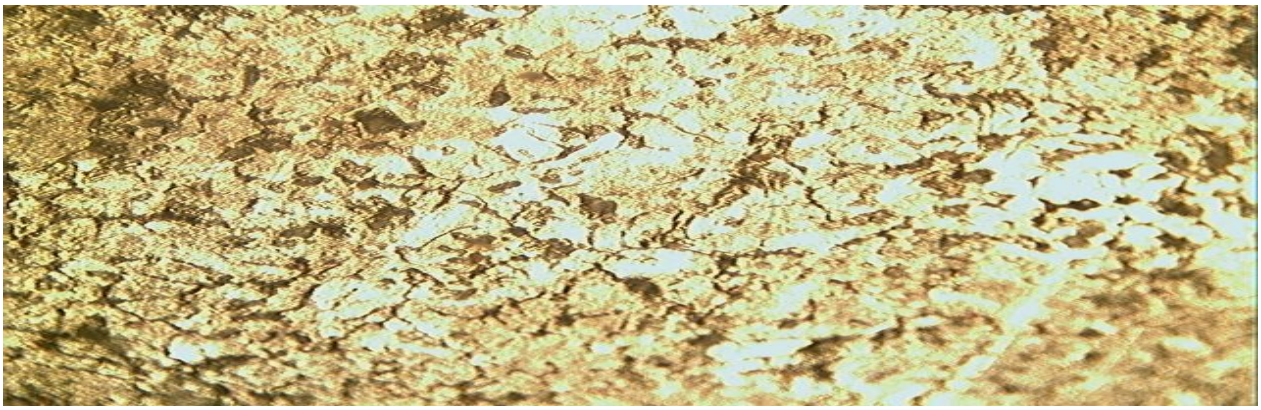


Plate XVIII: Microstructure of Al-5%Cu reinforced with 5wt%Gr peak aged at 300^{o}C showing more distribution of the compounds $CuAl_2$ and other compounds (dark) with graphite particles and break down of the dendritic structure in the Matrix (white) (X200). Etchant: acid etchant

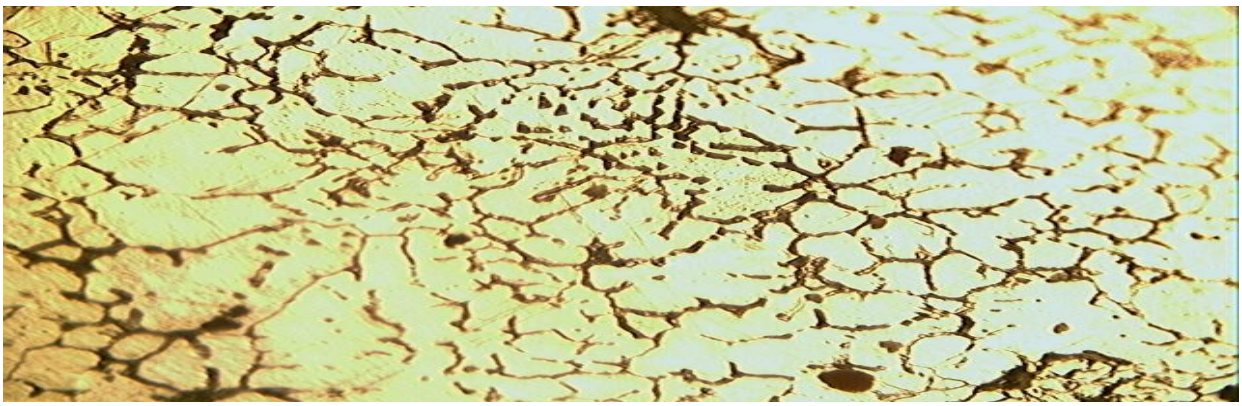


Plate XIX: Microstructure of Al-5%Cu reinforced with 7wt%Gr peak aged at 100^{o}C showing break down of the dendritic structure and distribution of the graphite particles at the grain boundaries with the $CuAl_2$ and other compounds in the Al-matrix (white) (X200). Etchant: acid etchant

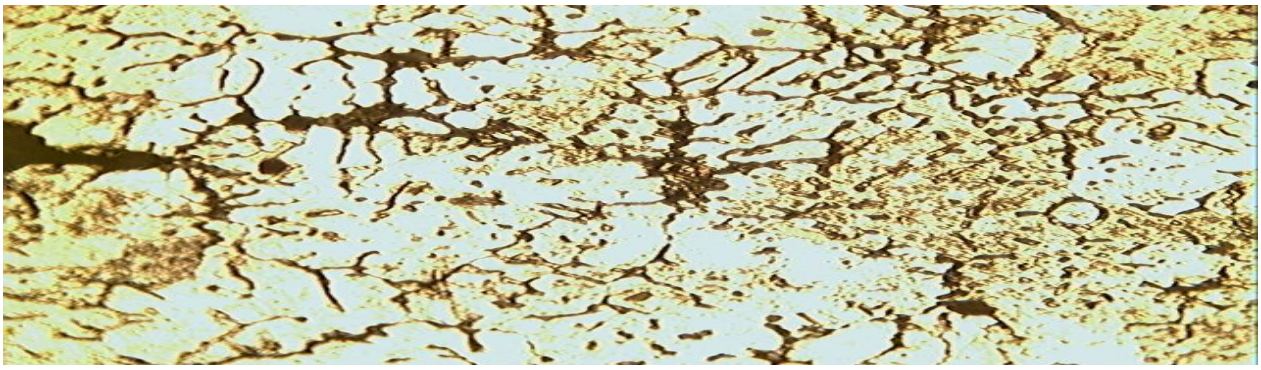


Plate XX: Microstructure of Al-5%Cu reinforced with 7wt%Gr peak aged at 200^{o}C showing the dendritic structure and distribution of the graphite particles along the grain boundaries with the $CuAl_2$precipitates and other compounds (dark) in the Al-matrix (white). (X200). Etchant: acid etchant

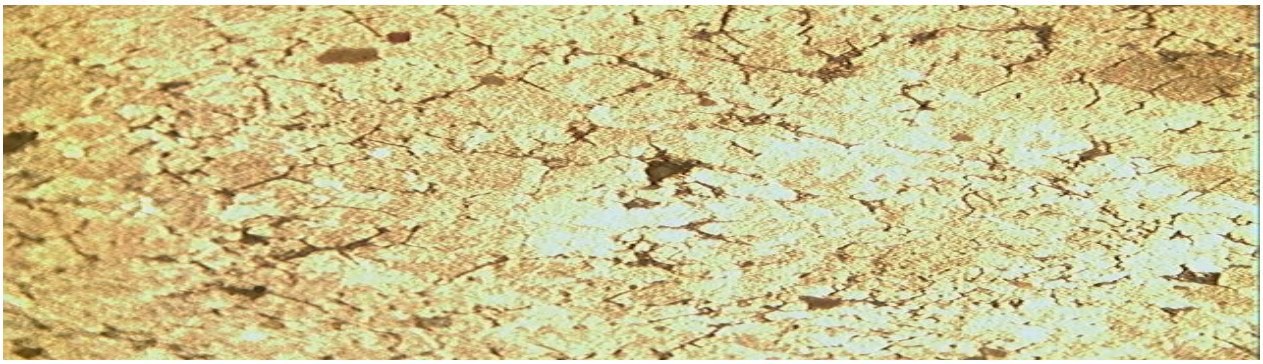


Plate XXI: Microstructure of Al-5%Cu reinforced with 7wt%Gr peak aged at 300^{o}C showing the precipitates of $CuAl_2$ and other compounds (dark) and the graphite particles along the grain boundaries in the Al-matrix. There is complete breakdown of the dendritic structure. (X200). Etchant: acid etchant

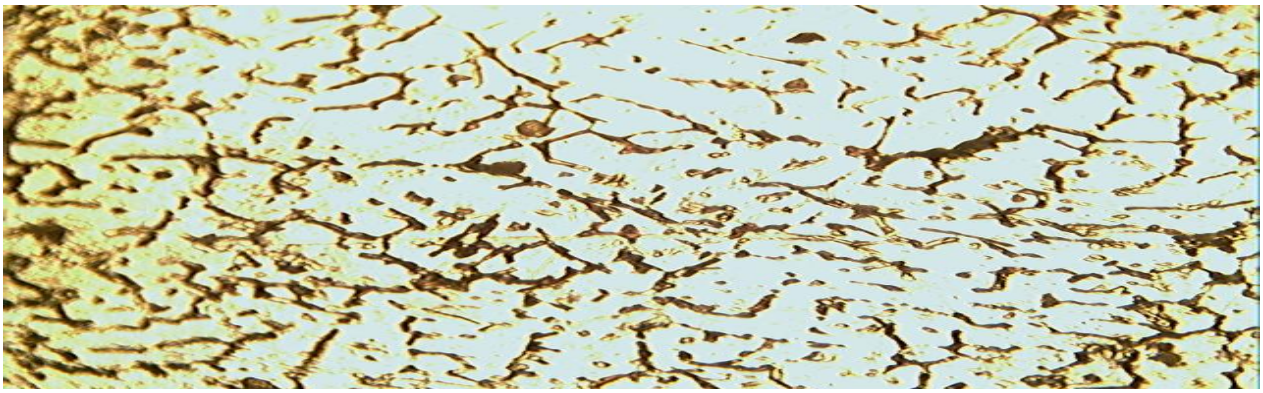


Plate XXII: Microstructure of Al-5%Cu reinforced with 9wt%Gr peak aged at 100^{o}C showing the breakdown of the dendrite structure and distribution of the $CuAl_2$ precipitates and other compounds in addition with the graphite particles (dark) in the Al-matrix (white) (X200). Etchant: acid etchant

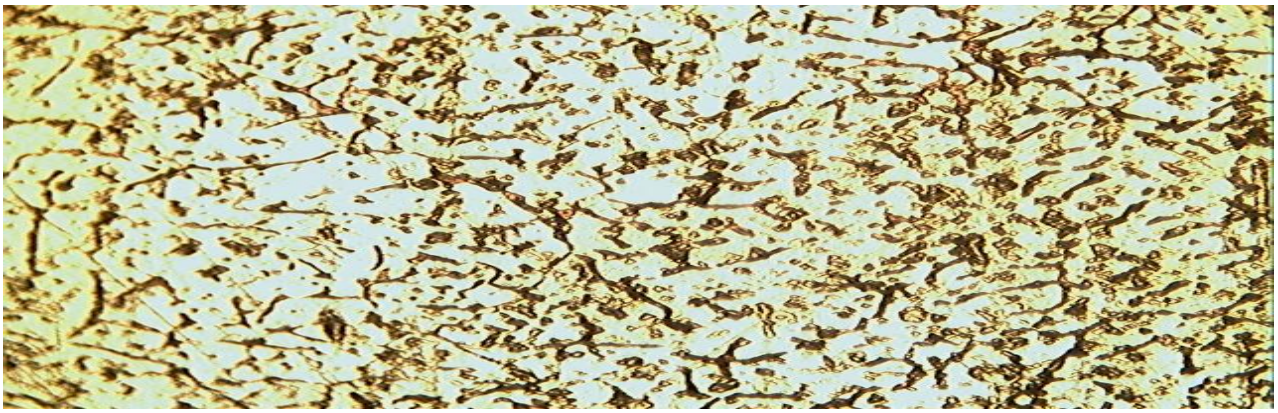


Plate XXIII: Microstructure of Al-5%Cu reinforced with 9wt%Gr peak aged at 200^{o}C showing more distribution of the graphite particles within the matrix and mostly along the grain boundaries in addition with the precipitates of $CuAl_2$ and other compounds (dark) in Al matrix (white) (X200). Etchant: acid etchant

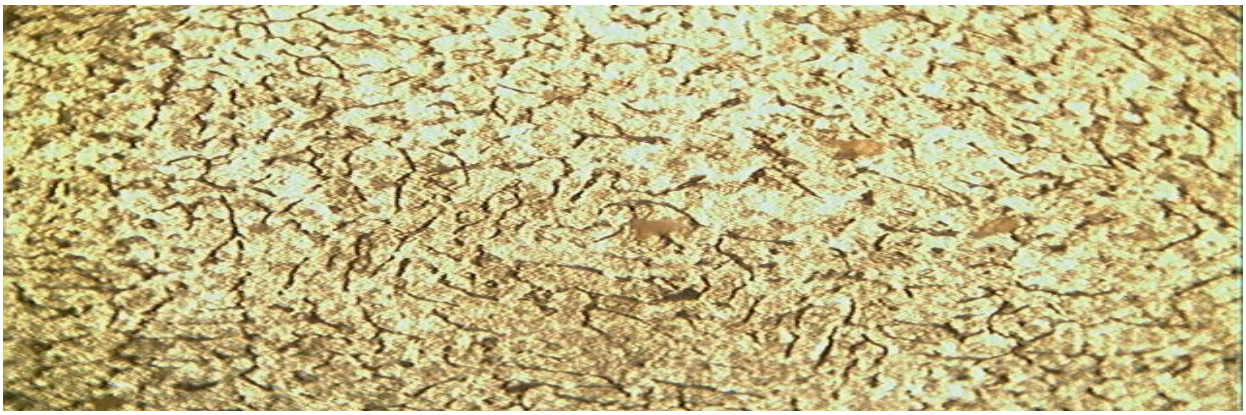


Plate XXIV: Microstructure of Al-5%Cu reinforced with 9wt%Gr peak aged at 300^{o}C showing more distribution of the graphite particles along the grain boundaries in addition to the $CuAl_2$ precipitates and other compounds in the Al matrix. (X200). Etchant: acid etchant

4.2 DISCUSSION

4.2.1 Microstructural Analysis

The microstructures of the as-cast and heat treated composites at various ageing temperatures and peak aged times were examined using the metallurgical microscope which is connected to a computer system. The structures consisted essentially of α-Al, Al-Cu ($CuAl_2$), intermetallic compounds as well as the graphite particulates which mostly existed at the grain boundaries due to segregation and rejection of graphite particles from the melt as captured in plates I-XXIV. The intermetallic phases formed could not be ascertained as optical microscopy can not be used to determine the various intermetallic phases formed.

The microstructure of the as-cast unreinforced alloy is shown in Plate I. It contains essentially a network of the θ phase ($CuAl_2$) and globules and plates typical of Al-Mg compound in the α-Al matrix.

Plates II-VI show the microstructures of the as-cast reinforced alloys with graphite particulates. The structures reveal a network of the $CuAl_2$ compound with the graphite particulates at the grain boundaries. However, plates V and VI show pronounced dendritic structures on solidification in addition to the contents of the micrographs which are at interdentritic regions.

Plates VII-XXIV show the microstructures of the age-hardened Al-5%Cu/Grp composites. The microstructures reveal the distribution of the graphite particles in the grain boundaries and the presence of fine precipitates of $CuAl_2$ in primary aluminium and undissolved intermetallic phases. The various micrographs of the age hardened alloys show a break down of the dendrites either partially or totally but where it existed, the compounds as well as the graphite particles are present in the interdentritic regions.

Prasad and Das (1991) reported that in Al-Cu alloys, the first phase to solidify is the primary aluminium in a dendritic manner followed by the solidification of the eutectic (Al- $CuAl_2$) phase in the interdendritic regions and that during solidification of the composite melt, graphite particles are pushed by the Aluminium dendrites in the last freezing zone.

In general, the phases present in aluminium alloys may develop various morphologies with resulting microstructures that can range from a simple monophase (solid solution) structure to various polyphase morphologies. The occurrence of these various morphologies which have a strong influence on properties depends on alloy concentration and solubility and how the phases form during solidification and/or solid state heat treatment (ASM Handbook, 2004).

4.2.2 Density

The result for the density of the produced composite as well as the unreinforced alloy is as shown in figure 4.1

The result shows that the density of the reinforced alloy decrease with increase in graphite particulate addition even though the difference is minimal and there was a slight increase in density after 3wt% graphite addition which finally decreases at 9wt% graphite addition. However, the reason for the increase at 3wt% graphite is not known. The general trend showed a decrease in the values for density.

Krishnan et al (1981) reported a progressive decrease in density of the produced composite using the UPAL process (between 2.72g/cm3 for the unreinforced alloy and 2.60 for composite with 3wt% graphite addition).

4.2.3 Apparent Porosity

The result for the apparent porosity is shown in figure 4.2. This result shows an increase and decrease in porosity as the graphite particulate increases. The values for the porosity fall between 2% for the unreinforced alloy and 6% for 9wt% graphite addition. Generally, there is a progressive increase in porosity as percentage addition of graphite increases. Akhlaghi and Pelasseyed (2004) reported 5-8% porosity while Jha et al (1989) reported an increment in porosity from 6.0% to 13.0%.

4.2.4 MECHANICAL PROPERTIES

4.2.4.1 Hardness Values

The hardness values of the Al-5%Cu/Grp composites in both the as-cast and heat treated conditions are as shown in figures 4.3 – 4.6.

From the figures, it is observed that the unreinforced alloy aged at 200^{o}C and 300^{o}C had pronounced hardness values above the reinforced alloy with graphite addition. However, at 3% Gr addition in the as-cast state, the highest hardness value (fig. 4.6) was recorded as 64.5HRB. The hardness values for the samples aged at 100^{o}C had better hardness values than those aged for 200^{o}C and 300^{o}C and also those of the as-cast condition. Generally, there was a wide scatter in the hardness values as seen in figures4.3-4.6. According to Krishnan et al (1981), the density, UTS, Hardness and %elongation of LM13 Aluminium alloy progressively decrease with increasing addition of uncoated graphite particles. However, the mechanical properties of up to 3 wt% Gr are found to be adequate for many tribological applications. Also, Pai and Rohatgi, 1978 reported that addition of graphite results in a decrease in the hardness of aluminium alloy. In addition, Seah et al (1995) reported a very little scatter of results for hardness and the reason they gave was that the addition of graphite causes a significant reduction in the hardness of the composite (ZA-27/Graphite particulate composites) because graphite is a soft dispersoids and its addition tends to soften the material. Furthermore, since there were some increments recorded in the hardness values when aged, it could be inferred that the Al-5%Cu/Graphite particulate composites responds to solutionizing and ageing treatments. This is in accordance with the work of Pai and Rohatgi who reported that solutionizing Al-

4.5%Cu/2.2%Gr using the pellet method resulted in an increase in the hardness from 25Rb in the case state to 30Rb after solution treatment and to 38Rb after ageing. Therefore, graphite – bearing copper-containing aluminium alloys respond to solutionizing and ageing treatments.

4.2.4.2 Impact Energy

The result for the impact energy with wt% graphite particulate addition for the as-cast and age-hardened conditions is given in figure4.7.

From the figure, it was observed that the impact energy for the as-cast condition is lowest at 3wt% graphite with a value of 0.54J while the maximum value was recorded at 7wt% graphite with a value of 2.8J. Various values were obtained in the age-hardened condition.

At peak aged temperature of 100^{o}C, the maximum value for the impact energy was 5.15J at 1wt% graphite which is incidentally the highest value among the samples. At 200^{o}C and 300^{o}C, we have the impact energy to be 4.07J each at 1wt% graphite addition. From the above, it implies that the highest value for the impact energy was 5.15J at 1wt% graphite at peak aged temperature of 100^{o}C.

4.2.4.3 Percent Elongation and reduction in Area.

The results for the percent elongation and reduction in area are presented in figures 4.8 and 4.9 respectively.

From the results, it was observed that; for the percent elongation in the as-cast condition, 5wt% graphite had the highest value of 5.58% while the highest value for the age hardened condition at 100^{o}C was 5.09% at 7wt% graphite. The highest value for the percent elongation was recorded at 7wt% graphite with a value of 7.73% at peak aged temperature of 300^{o}C. Seah et al (1997) observed that the ductility of ZA-27/Gr composites in the as cast state had greater values than the heat treated case. According to their observation, they reported that as graphite content is increased from 0 to 5%, the specimens heat treated for 1, 2, 3 and 4hrs show improvements in ductility of 33.9, 30.9, 51.6 and 32.6% respectively. The as cast (non heat treated) specimen showed an improvement in ductility of almost 60% which is even greater than the values for the heat treated specimens. They continued by reporting that their result was in contrast with the general

statements made by Hosking et al, Divecha et al and McDanels who believe that the ductility of discontinuous reinforcement MMCs deteriorate with increase in reinforcing content. The reason they gave was that it was probably due to the large concentration of graphite which serve to accelerate grain growth in the matrix material. Pillai and Pandey (1989) reported that % elongation decrease with increase in vol.% of graphite in both the cast and the forged composites. Their reason was that the decrease in ductility with increasing graphite is associated with increasing density of voids or cracks with graphite particles. Abubakre and Khan (2004) reported that %elongation of the composite (Al-Si/Al2O3) showed a considerable decrease compared to the unreinforced alloy due to considerable brittle nature of the produced composite since no coating or wetting agent was adopted for the reinforcement thereby making the strength of the interface to remain low and making the composite susceptible to brittle failure.

For the percent reduction in area, there were various results obtained in both the as-cast and age-hardened conditions showing increment in some and decrease in others as in the percent elongation.

4.2.4.4 Yield and Ultimate Tensile Strengths

The results for the yield strength and UTS of both the as-cast and age-hardened composites are presented in figures 4.10 and 4.11 respectively.

The as-cast samples have a maximum of 126.42N/mm^2 and 72N/mm^2 tensile and yield strengths respectively at 3wt% graphite addition. As with other properties presented above, the tensile and yield strengths do not follow a definite pattern in both the as-cast and age hardened composites. At 0% Gr, the tensile strength was 91.64N/mm^2 and the yield strength was 65 N/mm^2 and it then increases to 105.09 N/mm^2 when aged at 100^{o}C and the value decreases to 90.04N/ N/mm^2 at 200^{o}C then increased to 99.67 N/mm^2 at 300^{o}C.

Furthermore, the tensile strength was maximum with a value of 136.18 N/mm^2 at 1wt% Gr aged at 300^{o}C and the lowest value was recorded as 112.78 N/mm^2 in the as-cast condition.

At 3wt% graphite, the maximum value for the tensile strength was 126.42 N/mm^2 in the as-cast condition while the age hardened values were lower than the as-cast value.

At 5wt% graphite addition, the maximum value for the tensile strength was 102.29 N/mm^2 at 200^oC. 7wt% graphite addition has its highest value as 96.99 N/mm^2 at 100^oC.

At 9wt% graphite addition, the maximum value for the tensile strength was recorded as 136.42 N/mm^2 at 200^oC and the lowest value stood as 20.24 N/mm^2 at 100^oC. This case was very abnormal compared to the general values obtained above. The reason for this was not clear but it may not be unconnected to the fact that at the point of the test, the Insron machine gripped a region of weakness or with solidification defect. Where improvement in the UTS was recorded, it could probably be due to matrix strengthening that might have occurred due to grain strengthening following a reduction in composite grain size and the generation of a high dislocation density in the matrix as a result of the difference in thermal expansion between the metal matrix and the graphite reinforcement as reported by Seah et al (1997).

There were also variations in the values obtained in the yield strengths of the unreinforced and reinforced composites with graphite additions.

Based on the above results and discussion, a general note is outlined below:

1. The results could not be compared in totality with past work on Al-Gr composites due to the fact that little literatures are available to the best of my knowledge on the mechanical properties of the said composites. This is because most of the researchers on Al-Gr composites based their research on the wear characteristics and the anti-seizing or anti-friction applications of the composites since the most probable area of application of the Al-Gr composite is in bearing application and tribological (friction, wear and lubrication) application. However, where there were literatures for comparison, the compositions were very few to make meaningful comparison.

2. The research showed a general and wide scatter of results as reflected in figures 4.1 to 4.11. A similar case was reported and documented by Pepper and Penty (1974) who prepared Aluminium-Graphite composites by Liquid Phase Hot Pressing method.
3. It was observed that generally, as the percentage of graphite increases, the yield and tensile strengths decrease within the investigated range of values for both the as-cast and age-hardened composites. It was also reported and documented by Pillai and Pandey (1989) and the reason they gave for such behaviour was that "The decrease in tensile strength with increasing wt% graphite is apparently due to the fact that the graphite particles act as voids".

   Furthermore, the mechanical properties decreased generally with the additions of graphite particulate and there were some obvious increases that were recorded at various ageing times and temperatures. The results indicate that graphite containing Al-alloys respond to solutionizing and ageing treatments as reported by Pai and Rohatgi (1978) who also stated that this will permit the production of alloys with a range of strength and ductility to suit the desired application. They also reported that apparently, the presence of graphite decreases the strength since the addition of copper alone would lead to an increase in the tensile strength. However, for several anti-friction applications, properties of the graphitic aluminium alloys are adequate.

   According to Lin et al (1998), tensile properties of the composites decreased with increasing weight fraction of graphite particulate. This, according to them may be attributed to cracking at the matrix/particulate interface. While Pai and Rohatgi (1978), stated that graphite particles are generally present in the interdendritic regions instead of being present within the dendrites. Apparently, the graphite particles are pushed by the advancing solidification from (sic) into the last freezing interdendritic liquid.

Another reason for the behaviour of the results in that manner, according to a renowned researcher from India by name B.K. Prasad in the reply he sent me when I sought his assistance and opinion on why the results was "abnormal" he had the following to say "The dispersed graphite, being very weak and soft (1-2 Mohs), essentially behaves as a porosity in the alloy matrix. This is responsible for the deterioration in strength, ductility and hardness. The scatter in properties from one region/casting to the other could be attributed to the segregation of graphite in the melt/casting. You may be aware that the non-wetting characteristic of graphite due to high contact angle with the Al melt associated with density difference between the matrix and graphite lead to the segregation problem. The extent of segregation could be found by carrying out statistical analyses on interparticle spacing, particle size distribution and volume fraction distribution of graphite particles in different regions of a casting and different castings in a heat. The degree of scatter may increase after heat treatment due to swelling of entrapped gases and/or pores in the casting."

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

The research focuses on the development of Al-5%Cu/Grp composites by using uncoated graphite particulate of size 125μm through the liquid metallurgy route i.e. stir casting and then studying the mechanical properties in both the as cast and age hardened conditions. The Al MMC studied in this research contained 1,3,5,7 and 9% graphite particulate as well as that of the unreinforced alloy. The microstructures were evaluated following the standard metallographic method which entails grinding with grit papers, polishing, and etching using an acid etchant (2ml HF, 5ml HNO_3 and 100ml H_2O) and finally viewing under a metallurgical microscope which is attached to a computer system.

The hardness test was carried out using the hardness testing machine on HRB scale and the Hounsfield Balanced impact machine (Serial no. 3203) testing machine was used for the impact tests.

The Insron tensile machine was used to evaluate the tensile properties of the cast samples. All these tests were carried out on both the as-cast and heat treated conditions.

From the results obtained and discussion thereafter, the following conclusions can be made:

1. The use of 1%Mg is adequate to solve the wettability problem between aluminium alloy and graphite particulate but there is the probability that the lack of mechanical stirrer and degassers may be a reason why there was a wide scatter of results both in the as-cast and heat treated conditions and the distribution of graphite in the alloy is limited to the grain boundaries.
2. Stir casting method had been used successfully to produce Al-5%Cu/Gr particulate composites.
3. There was a general decrease in the hardness values of the reinforced alloys as compared to the unreinforced alloy since graphite particulates act as voids in the composite. Appreciable increase was recorded especially in the UTS in some compositions both in the as cast and age hardened conditions.
4. For the hardness values, aged temperature of $100^{o}C$ was best.
5. The study also indicates that the composite produced responded to precipitation hardening treatment as reported elsewhere.
6. Age hardening can be used to increase the mechanical properties of the composites at chosen compositions of graphite.
7. The Mechanical properties of the cast Al-5%Cu/Gr particulate composites are significantly changed by varying the amount of graphite particulate as well as by heat treatment.
8. In other to enhance the mechanical properties, a compromise is necessary when deciding how much of graphite particulate should be added and how long a heat treatment should be carried out.

5.2 RECOMMENDATIONS

From the results obtained in this present research the following recommendations can be given:

1. Further work should be carried out on this processing route for improvement in the properties as well as retaining of the graphite particulate in the matrix instead of being present at the grain boundaries. This could be achieved by using degassers such as dry Nitrogen gas or Hexachloroethane degasser tablets to neutralize the effect of the gas entrapment in the casting and also the use of mechanical stirrer.
2. The use of Al-Mg alloy or Al-Si alloy as the base alloy should be studied for possible improvement in the retention of graphite particles in the matrix.
3. Even though 1%Mg is adequate to solve the wettability problem, Magnesium content should be increased for better recovery of the particulate in the matrix.
4. Since the most probable area of application of this composite is in wear, tribology and anti-friction components, wear tests should be carried out so as to document the wear behaviour of the composites having evaluated the mechanical properties.
5. A hybrid composite should be developed where by the aluminium alloy would be reinforced with a high strength ceramic particle which would provide a higher mechanical property required for a particular area of application and soft graphite for lubrication and anti-seizing property.
6. Other tests can be performed on the composite such as fatigue, creep, thermal and electrical conductivities and damping capacity so as to have a complete documentation on the material.
7. If possible, particle size analysis should be carried out on the material so as to get an optimum range that will give better properties.
8. The Compocasting method of production should be explored for the composite since it eliminates most of the problems encountered during composite production
9. The use of SEM, Differential Scanning Calorimetry (DSC) and X-Ray Difractometer (XRD) should be carried out so as to get a full knowledge of the various intermetallic phases present within the matrix.
10. Having evaluated the necessary properties, a prototype of components should be produced to put it in test for possible improvement.

5.3 CONTRIBUTION TO KNOWLEDGE

Aluminium-graphite composite have been produced over the years but due to the problem of non-wettability of the graphite particles by the aluminium melt, coated graphite particles are being used to achieve this aim. This problem makes the whole process, expensive and difficult. At the end of this research work, these are the findings:

1. The addition of a reactive metal, in this case, Magnesium, to aluminium metal has helped to solve the problem of wettability in the production of Al-5%Cu/ Gr particulate composite.

2. There would be an eventual cost reduction since MMCs with particulate reinforcement can result in an increase in strength at a much lower additional costs than those of continuous reinforcements. Furthermore, the effect of reinforcement content on the aspect of ageing of MMCs has remained relatively unexplored and an understanding of such effects is vital to the design of composites. The age hardening behaviour of the produced Al-5%Cu/Gr particulate composites would be documented for further studies in future.

3. The production of Al-5%Cu/ Gr particulate composite can be used in areas of application involving wear resistance such as bearings, pistons, cylinder liners etc.

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APPENDIX: RESEARCH RESULTS IN TABLES

Table 1: **Density of the unreinforced and reinforced Al-5%Cu/Grp (g/cm^3)**

%Gr	Density
0	3.02

1	2.98
3	2.74
5	2.81
7	2.85
9	2.63

Table 2: Percentage Apparent Porosity of the unreinforced and reinforced

Al-5%Cu/Grp

%Gr	% Porosity
0	2.0
1	2.5
3	5.0
5	3.0
7	4.5
9	6.0

Table 3: Hardness Values with ageing times (Minutes) of the unreinforced and reinforced Al-5%Cu/Grp at 100^{o}C

%Gr/Time	60	120	180	240	300	360
0	36.6	30.1	27	23.4	20.6	30.1
1	44.1	41.3	40.9	39	37.1	32.6
3	25.8	38.4	39.4	30.6	23.6	35.7
5	35.5	43.1	30.4	48.8	45.8	41.2
7	32.3	40.1	24.3	29.5	31	31
9	43.3	34	42.3	41.3	35	33.5

Table 4: Hardness Values with ageing times (Minutes) of the unreinforced and reinforced Al-5%Cu/Grp at 200°C

%Gr/Time	60	120	180	240	300	360
0	66.7	77.3	76.4	72.3	70.4	68.4
1	36.6	36.2	35	38.1	36.6	28.3
3	29.8	41.9	28.5	25.8	24.8	22.4
5	43.2	46.7	39.9	39.5	33.7	30.8
7	26.2	23.3	35.9	39.3	31.7	29.8
9	42.1	44	41.2	38.5	36.7	34.6

Table 5: Hardness Values with ageing times (Minutes) of the unreinforced and reinforced Al-5%Cu/Grp at Al-5%Cu/Grp AT 300°C

%Gr/Time	60	120	180	240	300	360
0	69.3	77.8	63.5	68.1	74.5	68.5
1	38.4	37.6	37.1	30.8	29.9	26.9
3	23.9	35.2	32.3	25.4	20.8	25.7
5	33.2	33.1	34.3	33.9	33.6	32.4
7	24.4	21	33.4	28.5	29.3	27.5
9	37.7	40.3	43.6	39.2	35.5	32.5

Table 6: Hardness Values of the as-cast and heat treated Al-5%Cu/Grp

Composite (HRB)

%Gr	As-cast	100°C	200°C	300°C
0	41.3	36.6	77.3	77.8
1	26.8	44.1	38.1	38.4

3	64.5	39.4	41.9	35.2
5	33.4	48.8	46.7	34.3
7	26.3	40.1	39.3	33.4
9	25.5	43.3	44.0	43.6

Table 7: Impact energy of the as-cast and heat treated Al-5% Cu/Grp Composite (J)

%Gr	As-cast	100^{o}C	200^{o}C	300^{o}C
0	0.81	0.95	1.08	1.63
1	1.49	5.15	4.07	4.07
3	0.54	0.68	2.31	2.03
5	2.03	2.71	3.12	1.90
7	2.58	2.31	2.17	2.71
9	1.90	3.12	2.98	2.17

Table 8: Percent Elongation of the as-cast and heat treated Al-5% Cu/Grp Composite

%Gr	As-cast	100^{o}C	200^{o}C	300^{o}C
0	4.76	1.26	1.10	1.52
1	2.70	4.85	5.95	1.93
3	3.25	3.73	5.71	3.20
5	5.58	4.89	4.55	2.44
7	5.32	5.09	5.77	7.73
9	3.01	1.81	2.41	5.08

Table 9: The Percent Reduction in area of the as-cast and heat treated Al-5%Cu/Grp Composite

%Gr	As-cast	100°C	200°C	300°C
0	4.54	2.98	1.08	1.50
1	2.63	4.62	5.61	1.90
3	3.15	3.59	5.40	3.10
5	5.29	4.66	4.36	2.38
7	5.05	4.69	5.46	7.18
9	10.74	1.78	2.35	4.83

Table 10: Yield Strengths of the as-cast and heat treated Al-5%Cu/Grp Composite (N/mm^2)

%Gr	As-cast	100°C	200°C	300°C
0	65	48	65	58
1	64	48	65	58
3	72	52	6	27
5	33	41	71	58
7	50	53	50	56
9	63	19	64	68

Table 11: Tensile Strengths of the as-cast and heat treated Al-5%Cu/Grp Composite (N/mm^2)

%Gr	As-cast	100°C	200°C	300°C
0	91.64	105.09	90.04	99.69

1	112.78	120.50	129.08	136.18
3	126.42	86.24	67.60	80.69
5	79.18	57.04	102.29	78.42
7	56.96	96.99	93.44	96.69
9	123.16	20.24	136.42	102.36