DEVELOPMENT OF Al-Cu-SiC_p METAL MATRIX COMPOSITE FOR AUTOMOTIVE APPLICATIONS

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ABSTRACT

In recent years, the demand for reduced weight and high performance materials for automotive applications such as brake disc have increased. The newly developed, aluminium metal matrix composite (Al-MMC) reinforced with silicon carbide (SiC) particulate seem suitable to be an alternative material for this application. In this experimental study, Al-Cu-SiC_p MMC was developed through stir casting method with sand mould. A constant 4.5% of weight percentage of 5 μm pure copper powder was added to the mixtures to enhance the properties of Al-MMC. The effects of particle sizes of SiC as well as the weight percentage of SiC, pouring temperature and stirring time on the hardness, wear, compressive properties, flexure behavior and density of Al-Cu-SiC_p MMC were investigated. Taguchi's Robust Parametric Design was used with inner array L_9 3^4 and outer array with 2 replications to plan the experimental runs. A statistical Pareto Analysis of Variance (Pareto ANOVA) was employed to determine the significant factors of these properties and optimum combinations of process variables for targeted functions. From the analysis, it was found that particle sizes of SiC is the most significant factor for density characteristic and compressive properties while weight percentage of SiC is the most significant factor for hardness and wear resistance characteristics. Optimum combinations were determined and conformity test were conducted to verify the optimum properties of newly developed material, Al-Cu-SiC_p MMC. Optimum combination of hardness was $A_1B_2C_0D_0$ (*59 μm particle size of SiC, 15% of weight percentage of SiC, 675 ^{0}C pouring temperature and 5 minutes stirring time*) with 82.5 HV; wear rate $A_2B_2C_2D_0$ (*106 μm particle size of SiC, 15% of weight percentage of SiC, 725 ^{0}C pouring temperature and 5 minutes stirring time*) with 1.585 x 10^{-5} g/sec; compressive strength $A_1B_2C_2D_1$ (*59 μm particle size of SiC, 15% of weight percentage of SiC, 725 ^{0}C pouring temperature and 10 minutes stirring time*) with 9410.06 MPa and density $A_0B_1C_1D_1$ (*40 μm particle size of SiC, 10% of weight percentage of SiC, 700 ^{0}C pouring temperature and 10 minutes stirring time*) with 2.6592 g/cm^3.

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LIST OF SYMBOLS

Al-Cu-Mg	-	Aluminium-Copper-Magnesium
Al-Cu-SiC_p MMC	-	Aluminium-Copper-Silicon Carbide particulate metal matrix composite
Al-Li	-	Aluminium-Lithium
Al-MMCs	-	Aluminium metal matrix composites
Al_2O_3	-	Alumina
Al-Zn-Mg-Cu	-	Aluminium-Zinc-Magnesium-Copper
ASTM	-	American Society for Testing and Materials
BS	-	British Standard
DPS	-	Dual particle sizes
SiC	-	Silicon Carbide
SPS	-	Single particle sizes
Wt%	-	Weight percentage
B	-	Constant (Dimensionless wear coefficient)
F	-	Exerted force (N)
H	-	Hardness of the body
k	-	Spring stiffness (3.27kN/m)
n	-	Quantity of data taken
N	-	Rotational per minutes of rotating disc
Q	-	Volume removed per unit sliding
S	-	Sum of squares of differences
SN	-	Signal to noise ratio
V	-	Linear velocity of the disc (m/s)
W	-	Applied load (N)
Wa	-	Weight of specimen after experiment
W_b	-	Weight of specimen before experiment
W_l	-	Weight loss
x	-	Displacement of spring
y	-	Value of data from experiment (for instance, value og hardness

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CHAPTER I

INTRODUCTION

1.1 Introduction

In the recent years, the demand for light weight, low cost and high quality performance materials has increased. Many researches have been done to develop new materials that meet these requirements. One of the newly developed materials is aluminum metal-matrix composites (Al-MMCs). Basically, there are three types of MMCs: particle reinforced, whisker reinforced and continuous fiber MMCs.

Metal-matrix composite (MMCs) are widely used in industry because of their excellent mechanical properties. Nowadays, there are various products used of MMCs especially for automotive and engineering applications. This is because of their high strength, high elastic modulus, low co-efficient of thermal expansion, light weight, low thermal shock, good wear resistance and many more advantages. This combination of these properties are not available in a conventional material. These mechanical properties also depend on the composite particles for the reinforcement of the aluminium. Most of the alloys that were used as matrices are light alloys, particularly those based on aluminium (Abd El-Azim, *et al.* 2002).

Most researches on metal matrix composite (MMCs) in recent years has been concentrated on the development of high performance continuous fibre-reinforced composites for specialized applications. In spite of their unique properties, such composites are expensive. Therefore, development of less-expensive composites for non-critical applications is desirable. Particulate-reinforced MMCs are cost-effective alternatives and have the advantage of being machinable and workable using conventional processing method. However, their poor mechanical properties such as low fracture strain and fracture toughness, which are important for the design of structural materials, have limit their applications (Soon-Jik Hong, *et al.* 2003).

In this study, particulate-reinforced aluminum metal matrix composites (Al-MMCs) was emphasized. Aluminum acted as matrix component while the 4.5% copper (5 micron) and silicon carbide particles act as the reinforcement materials. In addition, Al-MMCs are relatively cheaper compared to other types of MMCs. Therefore, Al-MMCs are always being the first choice of material selections in industry's applications and attracting growing interest. In various industries, particularly the automotives and aerospace, application of aluminum alloy matrix composites reinforced with phases such as SiC or Al_2O_3 are increasing (S.Skolianos, 1996). It seems that Al-MMCs are in the right path to replace conventional materials such as cast iron in automotive industry especially in the braking system. Current drum and disk brakes are produced from gray cast iron. For instance, Lotus Elise has used Al-MMC as material for braking application while Chevy Corvette used it for automotive driveshaft.

Al-MMCs can be designed and engineered to perform most desirable properties in particular applications. This means that, the properties such as stiffness, density, strength, ductility and thermal properties of this material can be tailored or altered. This can be achieved by diversifying the matrix alloy, types of reinforcement, particle sizes, weight percentages, volume percentage and shapes of the reinforcement. By diversifying these factors, the distribution of the reinforcement material and bonding strength will be affected. Consequently, the mechanical properties such as tensile strength, toughness, hardness, density and wear resistance will also change significantly. Therefore knowledge of relationship and effects between mechanical properties of Al-MMCs and these factors are important to enable us to design desirable Al-MMCs.

There are three types of production methods in producing the Al-MMC. It includes liquid-state processing, solid-state processing and vapor-state processing. Among the variety of choices, stir casting method is the most suitable for large quantity of production. This liquid metallurgy technique is the most economical of all the available routes for MMC production and allows very large sized components to be fabricated (J.Hashim, *et al.*, 1999)

Particulate reinforced aluminium composites can be processed more easily by the liquid state i.e. melt-stirring process (K.M. Shorowordi, *et al.* 2003). Melt stir casting is an attractive process method since its advantages lie in its simplicity, flexibility and inexpensive casting compared to other method such as squeeze casting, spray casting and powder metallurgy. It is also offers a wide selection of materials and processing condition.

New development of aluminium based metal matrix composites with ceramic particles reinforcement for automotive application has a better future research. Although many researches are still done on particulate MMC, the mechanical properties are difficult to be predicted and measured because there are several factors that need to be considered during preparing of Al-MMC by this method. Appropriate testing, evaluation and better understanding on the properties and characteristics of the new developed material will be applied to provide better result and reliable data.

1.2 Backgrounds of the Problem

For the past few decades, conventional materials such as cast iron has played important role in automotive components. Gray cast iron, for instance, is used to produce automotive drum and disk brake, motor cylinders and pistons. The reasons why gray cast iron is more preferred; its low cost, good rigidity, good wear resistance, compressive strength and etc. However, gray cast iron is not a light material. This 'heavy' material will increase the fuel consumption of the vehicle. The market price of the petrol is increase continuously to the highest level in its history. Consequently, more money needs to be allocated for petrol by the car owners.

This study is based on the needs to find an alternative material for brake application material. The alternative material should not only be light weight but also has the properties such as high strength, hardness, toughness and wear resistance. The superior properties offered by particulate reinforced aluminium based MMCs make these materials attractive for automotive and engineering applications (Seah, *et al.* 2003). Al-MMCs specimens with various particle sizes and weight percentage of SiC were tested in order to determine its effect on the mechanical properties and other important characteristics of Al-MMC. By controlling the processing condition as well as the relative amount of the reinforcement material, it is possible to obtain a composite with a broad range of mechanical properties (J. Hashim, *et al.* 1999). Besides from that, the effect of additional reinforcement (copper) also will be determined. This will directly contribute to the performance of Al-MMCs as brake material, because of its tendency to alloy with aluminum and its higher thermal conductivity.

One of the superior characteristics of Al-MMCs is to allow its mechanical properties to be altered. This has established a need for better understanding of relationship between mechanical behavior and various factors such as particles sizes and percentage of weight of reinforcements.

Apart from that, the high production cost in preparing MMCs has also increased the needs to find other techniques which offer lower cost of production. Stir casting method is used in this study because of its low production cost compared to the powder metallurgy technique. The high cost of production process such as powder metallurgy has limited commercial applications of Al-MMCs (Hashim, *et al.*, 1999). It is hoped that this study will be a guideline for future research and applications of Al-MMCs produced via stir casting in other industries especially in automotive applications.

1.3 Statement of the Problem

This experimental study is aimed to find out the answer for the following questions:

(1) Is the newly developed Al-Cu-SiC_p MMC in this experimental study suitable to be an alternative material as disc brake material?

(2) What is the influence of particle sizes of SiC, its weight percentage, pouring temperature and stirring time to the wear, hardness, density and compressive strength of the Al-Cu-SiC_p MMCs?

(3) Which is the most significant factor which will affect the hardness, wear, density and compressive strength of Al-Cu-SiC_p MMCs?

1.4 Objectives Of The Study

The objectives of this research are to determine the significant effect of weight percentage, size of reinforcement particles, pouring temperature and stirring time to the mechanical properties of the newly developed material and to produce the Aluminium alloy based metal matrix composite using silicon carbide (SiC) and copper powder as the reinforcement particles through stir casting method.

1.5 Importance of the Study

As stated earlier, heavier vehicle will increase fuel consumption of the vehicle. Therefore, the usage of materials with reduced weight and higher performance in automotive components such as disc brake is vitally important. Lighter weight will ensure less fuel consumptions for the vehicle. One of the reduced weight materials is Al-MMCs. Al-MMCs' attractive properties include high strength, wear resistance, hardness and low density and so it seems suitable to be an alternative material for brake application.

This study also helps to highlight the usage and capability of stir casting method in preparing Al-MMC. Generally, stir casting method offers the most economical production cost and yields higher metals compared to other methods. Stir casting method also does not damage to the reinforcement. Results from the study will attract more interest of people in using this method in preparing Al-MMCs.

The experiment is conducted using the Taguchi's Robust Parametric Design approach by applying L_9 orthogonal array. Statistical analysis (Pareto-ANOVA) is applied to the results and findings manually. This approach is capable of determining significant factors which affects the properties of Al-MMC and determines the optimum conditions for maximum or minimum objective function.

1.6 Scope Of The Study

(i) Matrix material that used in this experimental study were Aluminium LM6 (A413) while Copper (99.7 % purity, 5 μm) and SiC particles (40, 59 and 106 micron) were used as reinforcement materials. Stir casting was performed by using portable electric furnace complete with stirrer and temperature controller.

(ii) Sand mould was used to produce the specimens according to the testing needs. The testing is done include hardness, wear, compressive strength and density.

(iii) Parameter design approach which applying L_9 orthogonal arrays was used to design the experiment. Statistical analysis method known as Pareto-ANOVA is used to analyze the data. Effect of noise factors is eliminated by repeating the experiment under each set of conditions.

(iv) The automotive application that will be emphasized in this study is brake disc.

CHAPTER II

LITERATURE REVIEW

This chapter reviews relevant literatures on metal matrix composites and its possibility for braking system application. Begin with overview of disc brake in Section 2.1. Then, Section 2.2 reviews the composites, and metal matrix composites in section 2.3. Factors affecting mechanical properties of Al-MMCs reinforced with SiC_p will be discussed in section 2.4. Manufacturing process of Al-MMCs reinforced with SiC particles in section 2.5. Relationship between wear loss and hardness will be in section 2.6 while section 2.7 reviews study of the influence of SiC on mechanical properties of aluminum metal matrix composites by other researches. For section 2.8, the comparison of studies is discussed. Section 2.9 reviews the gray cast iron and Al-MMC for automotive components. Section 2.10 reviews the Design of Experiment (DOE) with the summary of literature study in the last section.

2.1 Disc Brake

The optimization of automotive vehicles braking systems, subjected to mechanical and thermal stresses, depends on a combination of properties. In general, a complex state of stress is found and it is practically impossible to select a material and design a component based only on one of these properties. The material used in brake rotors should absorb and dissipate, as soon as possible, the heat generated during braking (G. Cueva, *et al.* 2003). Lately, reinforced aluminium has been introduced as disc material. Tribologically, this material works completely different from grey cast iron. The performance of aluminium disc is vitally dependent on the formation of a thick transfer film on the disc surface. On cast iron discs, thick transfer films must be avoided, as some wear of the disc is needed to remove oxides (Mikael Eriksson and Staffan Jacobson, 2000). Disc brakes are widely used for reducing velocity for their characteristics of braking stability, controllability and the ability to provide a wide-ranging brake torque. The braking processes in the friction units of a brake are very complicated. In the course of braking, all parameters of the processes such as velocity, load, temperature, physicomechanical and tribological characteristics of the materials of the couple, and the condition of contacts are varying with time. The frictional heat generated on the interface of the rotor and the pads can cause high temperature.

Particularly, the temperature may exceed the critical value for a given material, which leads to undesirable effect, such as the brake fade phenomena, local scoring, thermal cracking, and thermo elastic instability (C.H. Gao and X.Z. Lin, 2002).

During the last several decades, a great deal of effort has been devoted to improve the friction performance of brake rotor (or drum). The effort includes the development of non-ferrous material such as copper alloys, aluminium metal matrix composites (MMCs), and carbon composites as new candidates (M.H. Cho, *et al.* 2003). The material in the disc brakes are usually grey cast iron with 3-4 wt.% carbon. This material contains free graphite in the shape of small flakes in a pearlitic matrix. Traditionally, brake rotors are manufactured in grey iron class 250 (UTS_{min} = 250 MPa), with predominantly pearlitic matrix (>95% pearlite) (G. Cueva, *et al.* 2003). Besides having desirable thermal properties, grey cast iron has sufficient mechanical strength, satisfactory wear resistance, good damping properties, low cost, and it is also relatively easy to cast and machine (Mikael Eriksson, *et al.* 2002).

In the drive for better fuel economy and the need to offset the weight gains brought about by increasing automation, lighter weight materials are being investigated as potential replacement for steel automotive parts. The greatest savings are for rotational parts, such as brake disc or drum. Unfortunately, the wear resistance of aluminium is not sufficient for these applications, but with the addition of SiC particulate reinforcement it is possible to increase wear resistance while at the same time increasing specific stiffness and lowering thermal conductivity, all beneficial in terms of performance (S.M. Roberts, *et al*. (1998). Aluminium alloys containing silicon carbide can be considered as they afford a significant reduction in weight, although their inability to support high temperatures means that brakes have to be oversized, a factor which partly cancels out the weight advantage. Cast iron in one of its numerous forms therefore remains the preferred material.

The main purpose of a car brake is to reduce the speed. The two main functions of a brake disc or drum are the transmission of a considerable mechanical force and dissipation of the heat produced, that implies functioning at medium or high temperatures. In this process, the kinetic energy is transformed into heat by the frictional work. Friction makes rotors reach, during very small period of time, temperatures as high as 800 °C (1472 °F), resulting in the thermal gradient between the surface and the core of the rotors, which may reach up to 500 °C (932 °F) (G. Cueva, *et al.* 2003).

Car brakes experience dry sliding contact at roughly 50% of the speed of the car. A typical front brake pad is about 8cm long and 5cm wide and the brake disc has a diameter of 28cm. The pad covers around 10-15% of the corresponding rubbing surface of the disc. During normal, relatively soft braking the force pressing the pad against the disc is about 5kN, resulting in a nominal pressure at the pad surface just above 1.2 MPa. In extreme situations, the pressure could be close to 10 MPa. During hard braking, the power dissipation on the brake pad easily exceeds 30 kW. These high power densities result in very high surface temperatures and thus put special demands on the friction materials (Mikael Eriksson, *et al.* 2002).

For applications in the automotive, transportation, construction, and leisure industries, affordable cost is also an essential factor. 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 (Al-MMCs) because of their relatively low cost and isotropic properties especially in those applications not requiring extreme loading or thermal conditions (e.g., automotive components).

2.2 Composites

Composites are combination of two or more materials (constituents). Each of material has its own characteristic or identity. The purpose for this combination is to achieve particular function or characteristic and to rectify weaknesses possessed by each constituent. Generally, composites offer attractive characteristics that cannot possibly be performed by the single component itself. For instance, the present of SiC in aluminium composite has increased the strength of the composite. Without SiC, aluminium possesses lower strength. Composites can be classified into three classes depending on its matrix component. The matrix component will bind with reinforcement to produce composite. The classes of composites include metal matrix composites, polymer matrix composites and ceramic matrix composites. Polymer matrix composites are made from thermoset matrixes such as epoxies, polyester and and fenolic while typical ceramic matrixes for ceramic matrix composites are glass ceramic and alumina (Hashim, 2003). Figure 2.1 shows the classes of engineering material (Ashby, 1997). Metal matrix composites will be discussed in following section.

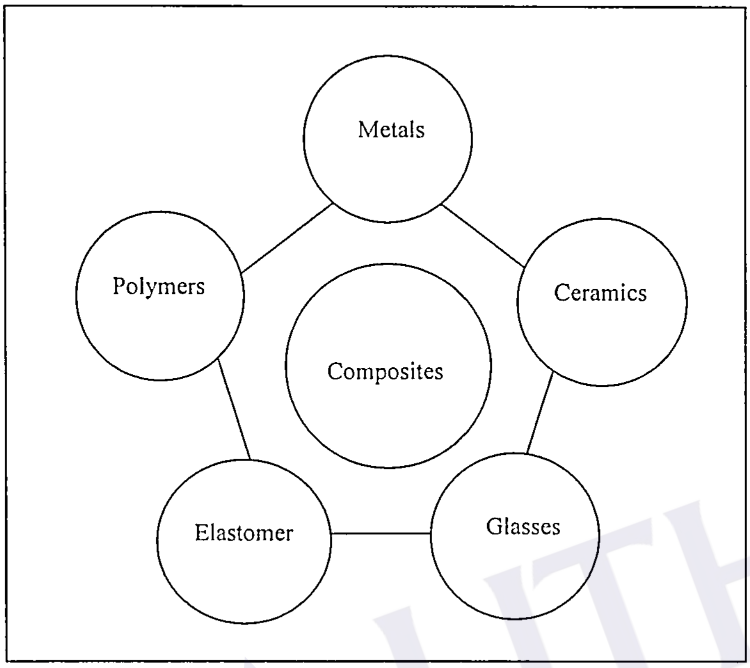

Figure 2.1: The classes of engineering material (M.F. Ashby, 1997)

2.3 Metal Matrix Composites (MMCs)

Over a few decades, metal matrix composites have emerged as one of the most promising material. Its unique, superior and potential improvement in mechanical properties has encouraged this material be the subject of scientific research. The excellent characteristics of metal matrix composites include being lightweight, high strength, low thermal and electrical conductivity, good fatigue strength and high specific modulus. However, these advanced materials are only widely used in particular industries especially in aerospace and automotive industry. Higher production cost has limited the usage of MMCs. Table 2.1 depicts some of the current applications of metal matrix composites.

In metal matrix composites, metal will act as a matrix component. The main function of matrix is to bind the reinforcement and to distribute the applied force evenly. While the reinforcement, typical ceramic can be in the form of particles, whiskers and continuous fibers. Hajri (2003) has classified ceramic reinforcement into two bigger groups namely continuous and discontinuous. He added, fiber reinforcement

Table 2.1: Applications of Metal Matrix Composites (Miracle, 2001)

	Component	System
Space	Antenna Waveguide Mast Microwave Thermal Packaging Power Semiconductor Base	Hubble Space Telescope Commercial LEO satellites Commercial GEO comsats
Automotive	Driveshaft Exhaust Valves Engine Block Cylinder Liner Brake rotor	Chevy Corvette, Pickup Toyota Altezza (Asian market) Honda Prelude Plymouth Prowler
Aeropropulsion	Fan Exit Guide Vane	Pratt & Whitney 4XXX engines
Aerostructures	Ventral Fin Fuel Access Door Covers Rotor Blade Sleeve	F-16 F-16 Eurocopter EC-120, N-4
Thermal Management	Power Semiconductor Baseplate	Motorola Power Chip
Recreation	Bicycle Frame Brake Fins	Specialized Stump-Jumper Disney Thunder Mtn Thrill Ride

can be either continuous or discontinuous reinforcement. Whiskers and particles are included in discontinuous reinforcement. Aluminium, titanium, magnesium and copper are typical important metallic matrixes that are frequently used in manufacturing MMCs. Silicon carbides, alumina and boron carbide are some of the reinforcement materials.

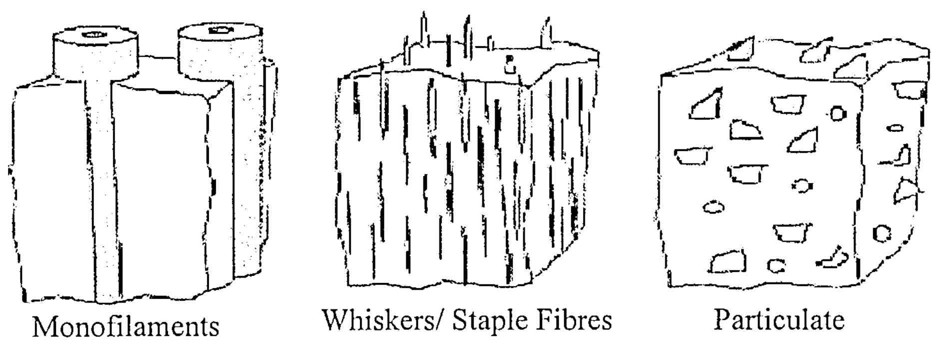

Figure 2.2: Types of MMC, Classified According to the Type of Reinforcement (Clyne and Withers, 1995)

Continuous-fibre reinforced MMCs provide the greatest improvement in stiffness (tensile modulus) and strength for MMCs. One of the first developed continuous-fibre MMCs was the aluminium alloy matrix-boron fibre reinforced system. The boron fibre for this composite is made by chemically vapour depositing boron on a tungsten-wire substrate. Al-B composite is made by hot pressing layers of boron fibres between aluminium foils so that the foils deform around the fibres and bond to each other. Other continuous-fibre reinforcements that have been used in MMCs are silicon carbide, graphite, alumina and tungsten fibres (Smith, 1996).

Discontinuous-fibre reinforced MMCs are produced mainly by powder metallurgy and melt infiltration process. In the powder metallurgy process, needle like silicon carbide whiskers about 1 to 3 μm in diameter and 50 to 200 μm long are mixed with metal powders, consolidated by hot pressing, and then extruded or forged into the desired shape. Although greater increases in strength and stiffness can be achieved with the whisker additions than with the particulate material, the powder and melt infiltration processes are more costly (Smith, 1996).

Particulate reinforced MMCs are low-cost aluminium alloy MMCs made by using irregular-shaped particles of alumina and silicon carbide in the range of about 3 to 200 μm in diameter. The particulate, which is sometimes given a proprietary coating, can be mixed with the molten aluminium alloy and cast into remelt ingots or extrusion billets for further fabrication. Applications for this material include sporting equipment and automobile engine parts (Smith, 1996).

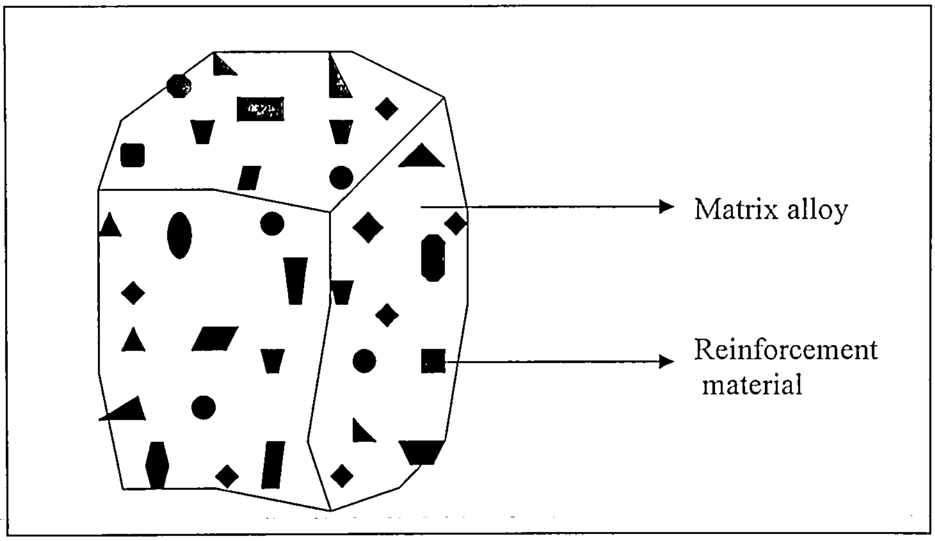

Figure 2.3: The schematic figure of particulate reinforced in composite material.

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