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.

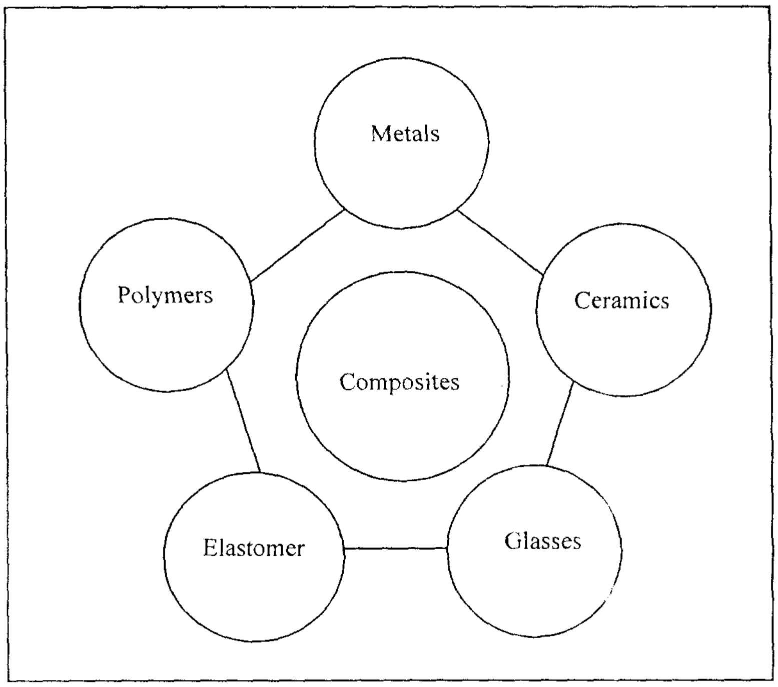


Figure 2.1: The classes of engineering material (M.F. Ashby, 1997)

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.

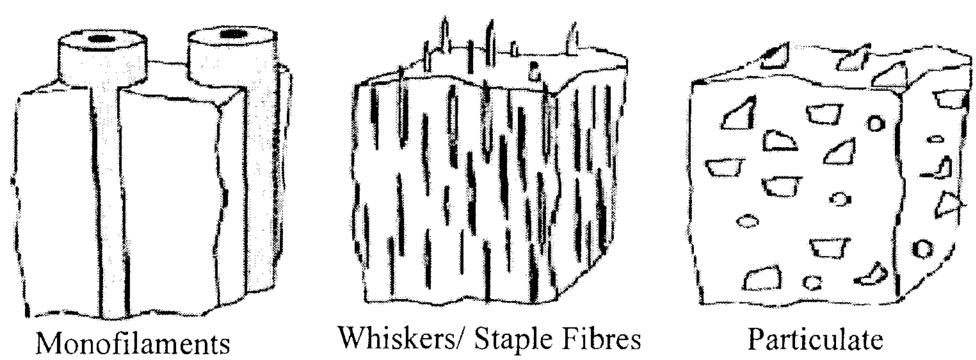


Figure 2.2: Types of MMC, Classified According to the Type of Reinforcement (Clyne and Withers, 1995)

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).

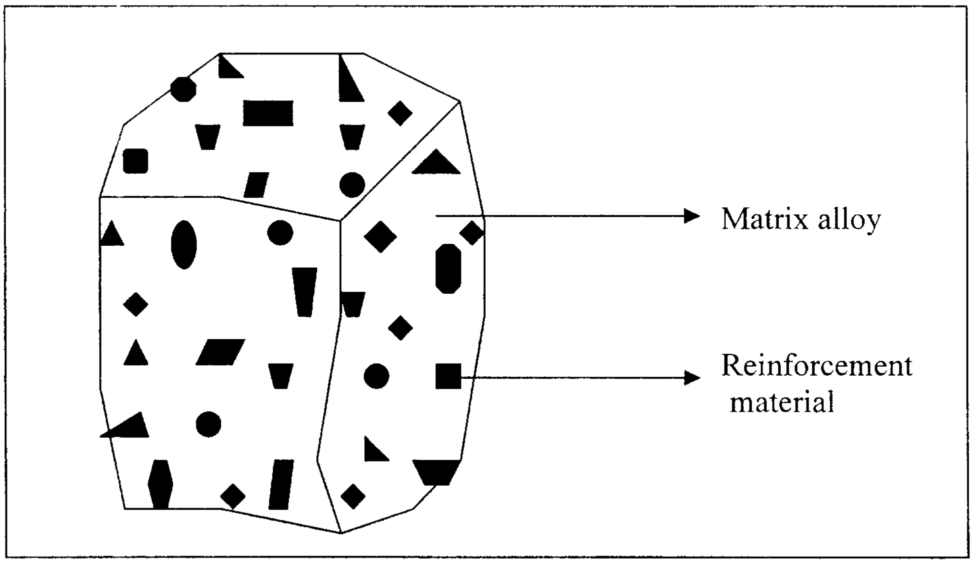


Figure 2.3: The schematic figure of particulate reinforced in composite material.

Among the MMCs, particle reinforced MMCs offer several advantages. According to Gur (2003), particles reinforced MMCs have advantages over other types of composites since they show isotropic behaviour, and can be formed using traditional metal working practices such as extrusion, rolling and forging. This is supported by Chawla (1993) in his study on metal matrix composites. He also suggested low production cost compared with continuous fiber reinforced as one of the advantages of particle reinforced MMCs. Below are some of the particle reinforced MMCs:

a) Aluminium MMC reinforced with silicon carbide particles
b) Copper MMC reinforced with boron carbide particles
c) Titanium MMC reinforced with titanium carbide particles
d) Magnesium MMC reinforced with Silicon Carbide particles

2.3.1 Aluminium Metal Matrix Composites Reinforced With Silicon Carbide Particles (Al MMC- SiC_p)

In this study, aluminium metal matrix composites reinforced with silicon carbide particles are chosen because of its low cost compared to others MMC. Moreover Al-MMCs are one of the most commonly used materials in industry. Al-MMCs offer high wear resistance, low thermal expansion and good corrosion resistance, which are suitable for automotive parts such as brake components. In addition, Al-MMCs also possess low density, good wear resistance and high strength. Therefore, these Al MMC-SiC_p have been found in many applications in aerospace and automotive industry (Sahin, 2003). However these advance materials also exhibit some disadvantages. For instance, in the presence of SiC particles, the ductility of Al-MMCs generally tend to decrease (Doel, et al., 1996)

Hajri (2003) mentioned that pure aluminum has low melting temperature (660^0C) in comparison to other matrix alloys. He explained that this will facilitate the processing of Al based MMCs by solid state and traditional casting. Examples of some of the aluminum alloys are Al-Cu-Mg, Al-Zn-Mg-Cu and Al-Li alloys. According to Chawla (1993), the Al-Li alloys perform higher elastic modulus and lower density, which is suitable to aerospace industry

For silicon carbide, it has different mechanical properties compared to aluminum alloys. Its properties include higher melting temperature, stiffness, strength and hard.

Schwetz (2000) has concluded that silicon carbide possesses extreme hardness, high abrasive power, high modulus of elasticity (450GPa), high temperature resistance up to above 1500°C and high resistance to abrasion.

By controlling the types and amount of aluminium alloys and its reinforcement, MMCs with desired properties can be produced. That is why, manufacturing process has to be done carefully. Hajri (2003) has reported that frequent problems encountered when fabricating Al alloy based MMC with SiC is the formation of Al_4C_3 at the carbide/matrix interface as a result of interfacial reaction between Al-MMC and SiC.

$$4Al + 3SiC \rightarrow Al_4C_3 + 3Si$$

He noted that, Al_4C_3 is brittle, unstable and capable degrading the mechanical properties of composites. He also suggested some of the methods to avoid formation of Al_4C_3. His suggestions are: addition of silicon to the matrix, coating SiC and passive oxidation of SiC

2.4 Factors Affecting Mechanical Properties Of Al-MMCs Reinforced With SiC Particles

The main purpose for developing Al-MMCs is to combine desirable attributes of matrix alloys and ceramic reinforcement. One of the important characteristics of Al-MMCs is its mechanical properties can be tailored or altered. To achieve the desirable properties, it is crucial to have substantial knowledge on the variables that can affect the mechanical properties of Al-MMCs. The variables or factors are: particles sizes of reinforcements, volume fraction of particulate, particle shape, pouring temperature, stirring time and stirring mechanism.

2.4.1 Particles Size of Reinforcements

The particle sizes of reinforcements play crucial role in determining the mechanical properties of Al-MMC. For instance larger ceramic particles give greater wear resistance. Garcia-Cordovilla, *et.al* (1995) and Bindumadhavan, *et.al* (2000) have clarified this in their study on wear behavior of Al-MMC. Further explanations will be included in section 2.6.

According to Clyne and Whithers (1995), particles fracture is a common problem for materials containing coarse particles while cracking are rare for materials with fine particles. This idea has been supported by Doel and Bowen (1996) in their study on tensile properties of particulate-reinforced metal matrix composites. The specimens that were used in their study were produced by spray deposition technique. In that study, it was found that 0.2% proof stress for Al alloy 7075 reinforced with 60μm SiC particles was lower than those reinforced with 5μm irrespective of the ageing condition. They explained the main reason for this result was the fracture tends to occur at coarse ceramic particles than smaller particles when at given applied stress. In other way, this means that 60 μm particles were more likely to fail at low applied stress than 5μm particles.

Besides proof stress, the elastic modulus was also affected by the particle sizes of reinforcement. Z.Gnjidic *et al* (2001) revealed that Al-MMCs (by powder metallurgy) reinforced with smaller particles size tends to exhibit higher value of elastic modulus. However, there was an exception for Al (CW67)-MMCs with 0.7μm which performs lower elastic value than larger reinforcement. Reason given by Z.Gnjidic *et al* was, it might due to the presence of SiC agglomeration in the composites. Consequently, the matrix surrounded by the agglomeration is subjected to higher stress and forced to yield. The matrix components cannot sustain higher stress.

Also, C.H.Gur (2003) in his investigation of microstructure-ultrasonic velocity relationship in SiCp-reinforced aluminium metal matrix composites (by powder metallurgy), found that the tendency of segregation in Al/SiC increased with the increasing Al/SiC particle size ratio. This is inhomogeneity distribution and will decrease the mechanical performance of Al-MMC. Meslet Al-Hajri (2003) indicates that as the particle size increases for a constant volume fraction, the inter-particle spacing increases and the dislocation density due to the coefficient of thermal expansion mismatch decreases.

2.4.2 Volume Fraction of Particulate

Sahin (2003) revealed that, the properties of Al-MMCs depended not only on the particle sizes but also on the volume fraction of particulate reinforcement. In his study, results indicate that the hardness and density of Al-MMC (by molten metal mixing and squeeze casting) increased with the increasing of volume fraction of particulate. However the porosity level shows the other way with increasing SiC content.

As for wear property, Garcia-Cordovilla, *et.al* (1995) and Bindumadhavan, *et.al* (2000), Miyajima and Iwai (2003) have concluded that better wear resistance will be achieved when the amount (volume) of SiC_p is increased. Jamiliah Idris, *et.al* (2003) also suggested the same theory in their study on wear and hardness properties of Al-MMC fabricated by powder metallurgy technique. Other conclusion from them was that the wear resistance is proportional to the hardness of Al-MMC

2.4.3 Particles Shape

Miyajima and Iwai (2003) showed that shape of reinforcements will also affect the wear resistance of Al-MMC. 3 types of reinforcements were compared: particle, whisker and fiber. They found that particle reinforcement was the best in improving the wear resistance of Al-MMC.

Figure 2.4 depicts the plots of true strain versus void content of $Al\text{-}Al_2O_{3p}$ for MMCs with angular and spherical particles. From this figure we can determine that the shape of reinforcement have effect on the percentage of void content. In addition, Clyne and Withers (1995) also explained that crack preferentially occurs at elongated particles.

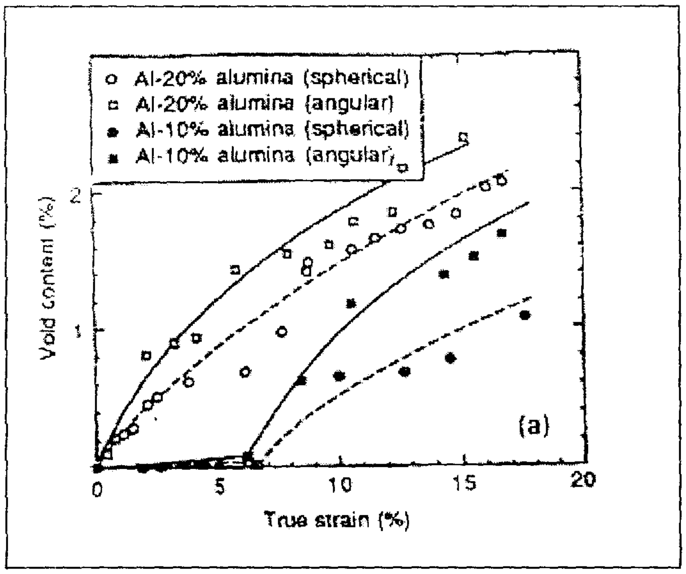


Figure 2.4 : Plots of True Strain versus Void Content of $Al\text{-}Al_2O_{3p}$ (Clyne and Withers, 1995)

2.4.4 Pouring Temperature

Fareed (2002) found out that pouring temperature has effects on the mechanical properties (wear, toughness and hardness) of Al-MMCs. However inconsistent data were drawn from the experiment. Jananee (2004) also mentioned that the mechanical properties of Al-MMCs were affected by the pouring temperature. In her study, she concluded that, the increase in pouring temperature will reduce the hardness and toughness but increase the average wear in the cast composite. The discrepancies between both studies may be due to the differences of pouring temperature selected for both studies. Jananee used 850°C and 900°C while Fareed used 750°C, 800°C and 850°C.

2.5 Manufacturing Process of Al-MMCs Reinforced With SiC Particles

Manufacturing process of Al-MMCs reinforced with SiC particles can be classified into 3 categories: solid-state processing, vapor-state processing and liquid-state processing.

Powder metallurgy is typical solid state processing method. This method involves 3 steps: mixing of matrix and reinforcement powder, compacting the mixture and finally the sintering process is applied to the compact mixture.

For vapor state processing, deposition technique is used. However this method is used mainly for fiber reinforcement. Furthermore, this method has its own disadvantage, which is higher cost of production.

There are many liquid state processing techniques available. It includes squeeze casting and stir casting. Squeeze casting technique is shown in Figure 2.5.

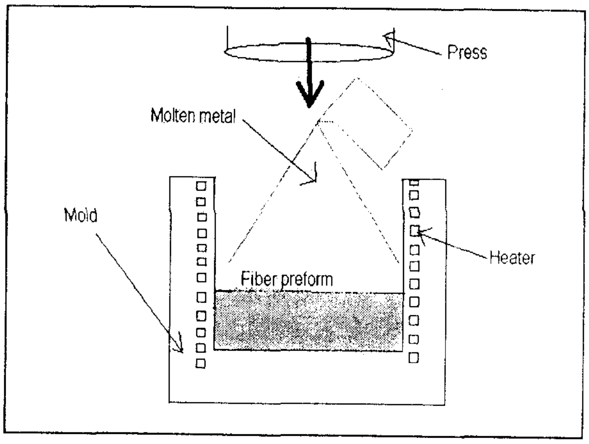


Figure 2.5: Squeeze Casting Process (Chawla, 1993)

Stir casting technique will be discussed in following section. The classifications of the manufacturing methods and other examples in processing MMC are depicted in Figure 2.6.

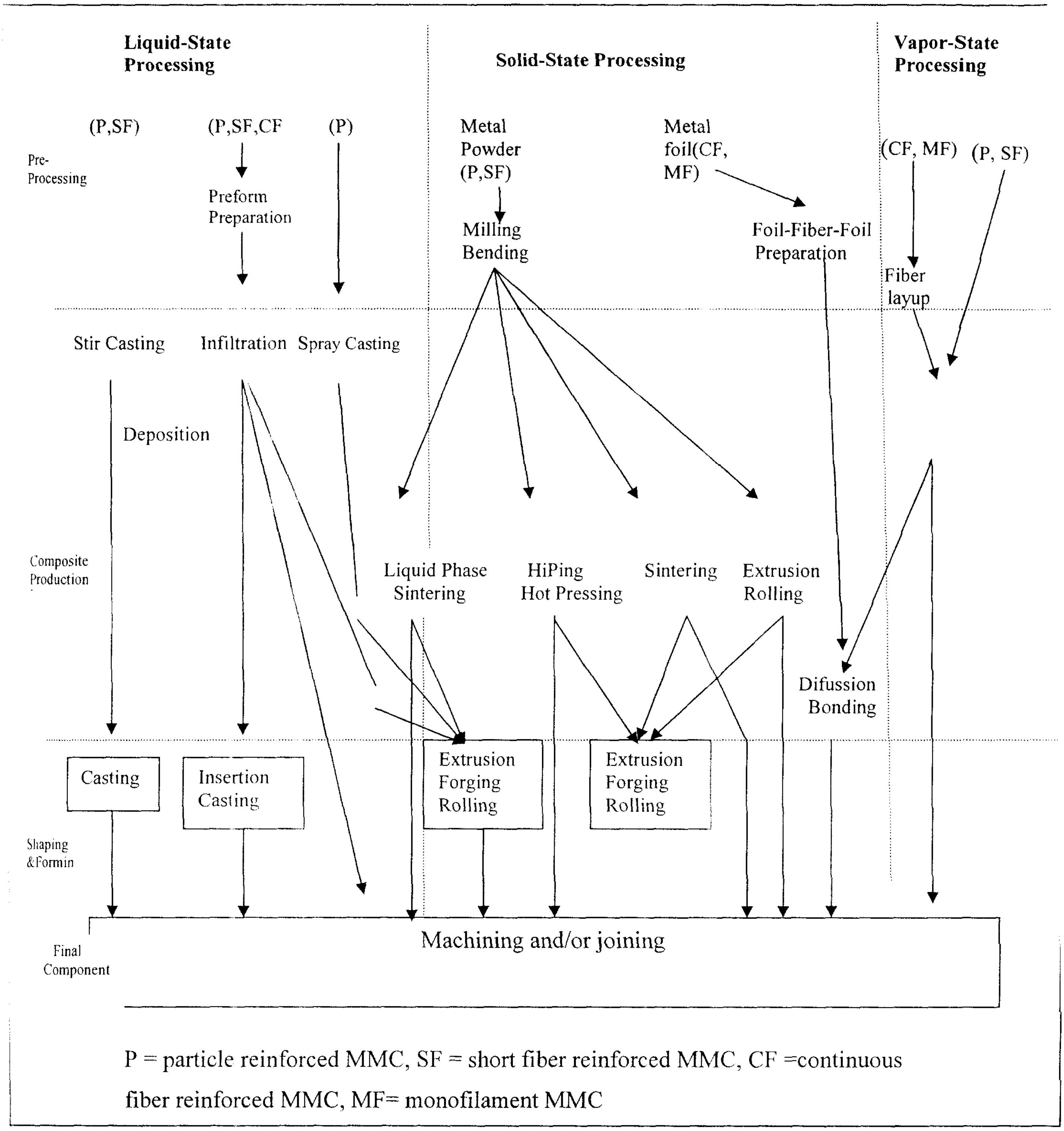


Figure 2.6: Overview Flow Chart of Processing Routes for Metal Matrix Composites (Hajri, 2003)

Each of the process has its own limitations and advantages. For instance, powder metallurgy offers greatest flexibility in choice of particle sizes and reinforcement but it also probably is the most expensive technique (Gur, 2003). In this study, only liquid state processing (stir casting) technique will be explained

2.5.1. Liquid-State Processing (Stir Casting)

High cost of production has generally limited the use of Al-MMC in commercial applications. However, stir casting method offer lower production cost. Furthermore, it advantages lie in its simplicity, flexibility, applicability to large quantity of production and allows large size of the components to be fabricated (Hashim *et al*, 1999). These advantages have lead to the usage of stir casting in this study.

Stir casting process involves 4 steps. It begins with melting the matrix alloy (aluminum alloys) in a furnace. Then, the ceramic reinforcement (SiC) will be added to the molten matrix alloy. Later, stirring process will take place and finally the melting is transferred to the mould. The specimen is ready when the solidification completes.

2.6 Relationship Between Wear Loss and Hardness

Relationship between wear loss and hardness is represented in Archard equation (Clyne and Whithers, 1995),

$$Q = \frac{BW}{H} \qquad \text{(Equation 2.1)}$$

Q (m^2) = volume removed per unit sliding distance
W (N) = applied load
H (Pa) =Hardness of the body
B = Constant (Dimensionless wear coefficient)

From equation 2.1, we can conclude that the wear rate increases as the contact load is raised and hardness value falls.

2.7 Study of the Influence of SiC on Mechanical Properties of Aluminium Metal Matrix Composites by others Researches

This section will reviews selected studies done by the researches regarding on Al-MMCs. The researches are Garcia, *et.al*, Bindumadhavan, *et.al,* Miyajima and Iwai and Sahin.

2.7.1 Study on Abrasive Wear Resistance of Aluminium Alloy/ Ceramic Particulate Composites.

Garcia-Cordovilla, *et.al* (1995) in their study, have investigated the abrasive wear resistance of A357/SiC, A339/SiC, AA6061/SiC and AA6061/Al_2O_3 with different size and volume fraction of reinforcement. Comparisons with gray cast iron were also carried out by them. The samples used for this study were fabricated by compocasting method. Others experiment conditions were 4.9N normal load, 240m sliding distance and constant velocity of 60mm/s. SiC Grit 320 (Buehler) was used as abrasive paper. The result from this study is shown in table 2.2.

Results obtained from this experiment were inline with the theory that say, the wear resistance of composites increases as the volume fraction of reinforcements increases. For influence of particle sizes of SiC, it shows that larger particles will enhance the wear resistance of composites. Garcia, *et.al* (1995) explained that, larger SiC particles will remain embedded longer in composites since the interfacial between matrix and particulate become lesser as the particle sizes increases. Morphology observation was also done by Garcia, *et.al* and they found that worn surface of monolithic material exhibit long continuous groove while smooth worn surface of monolithic material exhibit long continuous groove while smooth worn surface was detected from composites with higher volume fraction of SiC_p For relation between wear resistance and Brinell hardness, Garcia, *et.al* found that relative wear rate of A339 and A357 composites increases with the inverse of theii

Table 2.2: Result of Abrasive Wear Resistance Of Al-MMC, Aluminium and Cast Iron (Garcia, *et.al*,1995)

Alloy	Particulate			P(g/cm^3)	Δ P (mg)	Δ V(mm^3)	BH	R_a(μm)
	Type	Grit	V_f (%)					
A357	-	-	0	2.68	17.1	6.4	63.3	1.73
	SiC_g	G400	10	2.73	8.76	3.2	73.8	0.72
			15	2.76	5.05	1.8	81.3	0.32
			20	2.79	2.9	1.0	90.7	0.23
	SiC_g	G600	15	2.76	7.72	2.8	73.2	-
A339	-	-	0	2.69	10.9	4.1	111	1.26
	SiC_g	G400	15	2.77	3.75	1.4	137	0.15
		G500	15	2.77	5.64	2.0	130	0.19
	SiC_b	G400	15	2.77	3.1	1.2	136	0.18
		G500	15	2.77	2.8	1.0	140	0.18
AA6061	-	-	0	2.71	15.4	5.69	71	0.96
	SiC_g	G400	15	2.79	5.64	2.02	71.5	0.86
	Al_2O_3		13	2.87	10.6	3.68	72.6	0.51
Cast iron disc	-	-	-	7.12	15.9	2.2	191	0.47
A357 disc	SiC	G400	13	2.76	6.3	2.3	87	-

* SiC_g = green SiC, SiC_b = black SiC, V_f = Volume fraction, P= density, Δ V= volume loss, Δ P= weight loss, BH= Brinell hardness. R_a= Surface roughness

relative hardness. Besides from that they also concluded that the wear resistance of Al composites and gray cast iron are similar. The advantage of Al composites is, it has lower weight than gray cast iron.

2.7.2 Study on Dual Particle Sizes (DPS) Composites: Effect on Wear and Mechanical Properties of Particulate Metal Matrix Composites

Bindumadhavan, *et.al* (2000) investigated wear, hardness and impact properties of aluminium alloy (A356) particulate reinforced metal matrix composite. Apart from that, metallography observation is also included in this study. Stir casting was used in this study while the speed of stirrer was fixed at 300-400 rev/minute. Table 2.3 depicts types of specimen used in this experiment.

Table 2.3: Type of Specimen Used (Bindumadhavan, *et.al,* 2000)

Specimen	Volume of SiC (%)	Particle size of SiC
1) Single particle size (SPS)	a) 3 b) 7 c) 11 d) 15	→ 47μm
	e) 3	120μm
2) Dual Particle Size (DPS)	a) 3	47μm (2vo.%), 120 μm(1vol. %)

Dry ball sliding wear test was conducted in this experiment. Silicon nitride has been chosen as a counter face material. Other conditions applied were 2 and 5 N normal load, 4 cm/s sliding speed and 564m sliding distance. Besides from that, optical microscope and scanning electron microscope were used for metallographic observations.

Bindumadhavan, *et.al* found that composite shows better wear resistance than unreinforced material. He also revealed that, silicon phase fragmentation at the worn surface of reinforced material is lesser than unreinforced material. Hardened layer is formed due to this fragmentation. Higher depth of this layer will lead to higher wear loss. With the presents of SiC_p in the composites, it will provide shielding to the silicon phase from directly experiencing the sliding force. Besides from that, SiC_p will also relieve the shear strain that occurred at the subsurface of material. Finally, this entire factor will directly increase the wear resistance of composites.

From Figure 2.7, we can conclude that higher amount of SiCp will increase the macrohardness of single particle size (SPS) composite. On other hand, Figure 2.8 shows the influence of sliding load and volume percentage of SiC_p to the weight loss of single particle size (SPS) composites. The result of comparative wear tests on single particle size (SPS) and dual particle sizes (DPS) composites is depicted in Table 2.4.

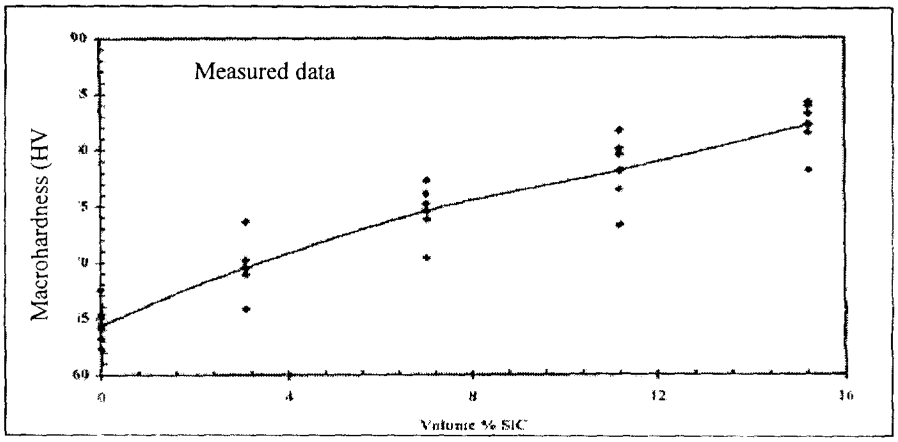


Figure 2.7: Plot of Measures Macrohardness of Single Particle Size (SPS- 47μm) Composites with Vol.% SiC (Bindumadhavan, *et.al*, 2001)

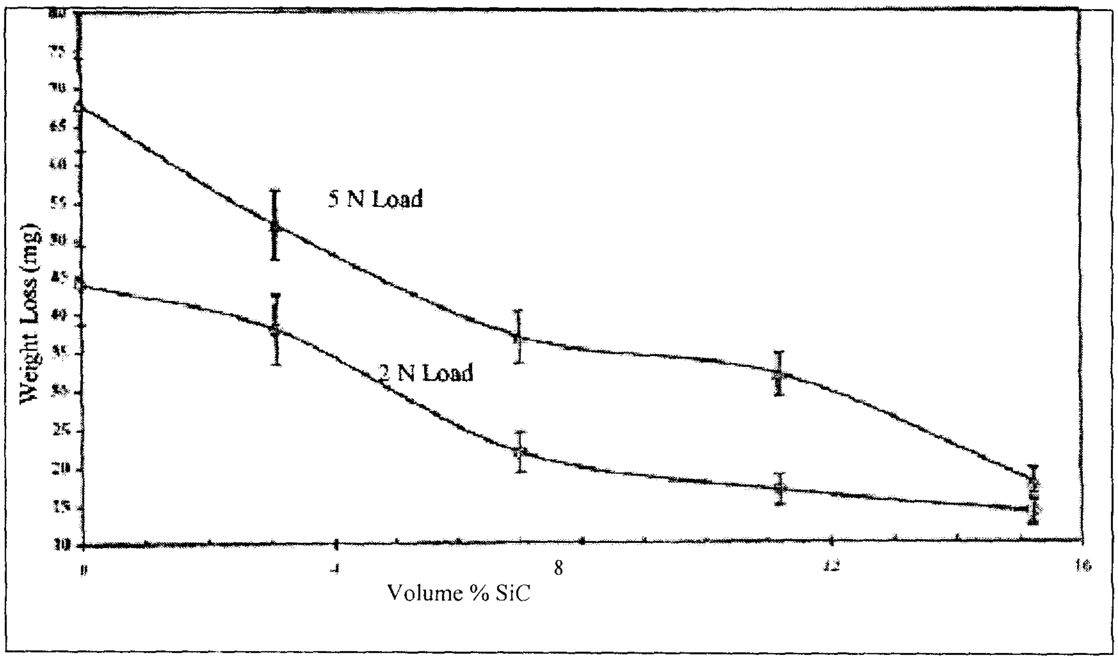


Figure 2.8: Plot of Weight Loss after Wear Test for Single Particle Size (SPS –47μm) Composites with Vol. % SiC and Test Load (Bindumadhavan, *et.al*, 2001)

From Table 2.4, it is shown that, dual particle size (DPS) composites exhibit lower wear loss compared to single particle size (SPS-47μm) composite. Bindumadhavan, *et.al* explained, larger SiC_p(120μm) tends to provide shielding to smaller SiC_p and this will prevent the SiC_p from gouging action. It will also lower the load applied to the smaller SiC_p and the matrix. The lowest wear loss experienced by single particle size (SPS) 3% vol. (120μm) composite in this study also clarify the theory that larger particle sizes of SiCp will increase the wear resistance of composites.

Table 2.4: Results of Comparative Wear Tests on Single Particle Size (SPS) and Dual Particle Size (DPS) Composites (Bindumadhavan, *et.al,* 2001)

Load (N)	Composite type (values are in weight loss in mg)		
	SPS 3% vol. (47μm) composite	DPS Composite (47μm + 120μm)	SPS 3% vol. (120μm) composite
2	32	21	15
5	47	30	20

Table 2.5: Results of Comparative Macrohardness Measurements on Single Particle Size (SPS) and Dual Particle Size (DPS) Composites (Bindumadhavan, *et.al,* 2001)

Composite Type	Macro hardness (HV) 20 kgf		
	Maximum	Minimum	Average
SPS 3% vol. (47μm) composite	65.2	60.8	63.7
DPS Composite (47μm + 20μm)	58.5	52.6	54.9
SPS 3% vol. (120μm) composite	49.8	41.2	45.2

From the Archard equation stated in section 2.6, wear loss will increase as the hardness fall. However, it seems that this does not happen in this study. Single particle size (SPS) 3% vol. (47μm) composite with highest wear loss exhibits maximum hardness value among the materials tested. Explanation given by Bindumadhavan, *et.al* was larger SiC_p in dual particle size (DPS) composites provide shielding protection to smaller SiCp during the sliding action. And it will reduce the wear loss of dual particle size (DPS). Impact test was also carried out but will not discussed here.

2.7.3 Study on Effects of Reinforcements on Sliding Wear Behavior of Aluminium Matrix Composites

The study on effect of reinforcements on sliding wear behavior of Aluminium Matrix Composites was performed by Miyajima and Iwai (2003). Pin-on-disk tests was used to determine the effect of various types of reinforcements on wear behaviour of Al-MMCs. The schematic view of test apparatus used in this study is illustrated in Figure 2.9.

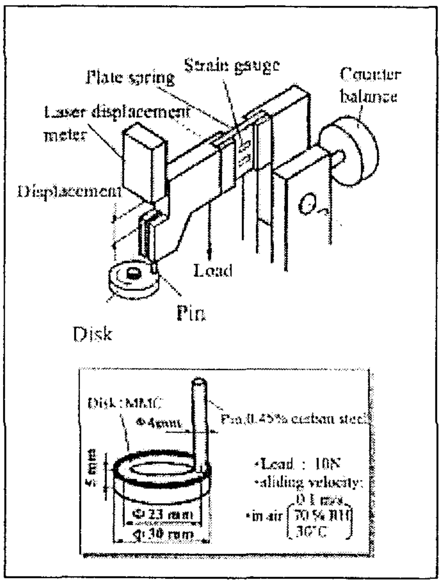


Figure 2.9: Schematic View of Test Apparatus (Miyajima and Iwai, 2003)

Objective of this study was to determine the influence of types and volume fraction of reinforcement to wear behaviour of MMC. Metallography observation was also done in this study. Test materials that used are depicted in Table 2.6.

Table 2.6: Types of Test Materials Used (Miyajima and Iwai, 2003)

Reinforcement	**SiC-Whisker**						
Matrix Material	2024Al						
Heat Treatment	T4						
Manufacturing Procedure	Powder Metallurgy				HPI (High Pressure Infiltration		
Length of Reinforcement	-	5-15			-	5-15	
Diameter of Reinforcement	-	0.3-1.0			-	0.3-1.0	
Volume Fraction of Reinforcement, V_f (%)	0	5	10	16	0	22	29
Reinforcement	**Al2O3-fiber**						
Matrix Material	ADC12						
Heat Treatment	-						
Manufacturing Procedure	High pressure, low speed die casting technique						
Length of Reinforcement	-	200	200	100	100	50	40
Diameter of Reinforcement	-	4					
Volume Fraction of Reinforcement	0	3	5	10	15	19	26
Reinforcement	**SiC-particle**						
Matrix Material	2024Al						
Heat Treatment	T6						
Manufacturing Procedure	PM						
Length of Reinforcement	-		-				
Diameter of Reinforcement	-		10				
Volume Fraction of Reinforcement	0		2		5		10

In this study, Miyajima and Iwai (2003), classified 2 stages of wear process: initial wear regime and steady state wear regime. They explained MMC with low volume fraction, V_f will experience higher wear loss in early stage of the test. The transition from initial to steady stage condition can be determined based on the changing of the slope of graph in volume loss versus sliding distance graph.

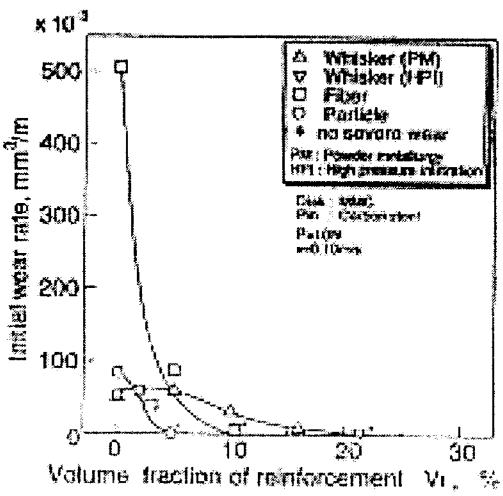


Figure 2.10: Wear Rates of MMCs (Disk Specimen) in initial Wear Regime as Function of Volume Fraction,V_f (Miyajima and Iwai, 2003)

From Figure 2.10, we can conclude that initial wear will decrease with the increasing of volume fraction of SiC_p. When volume fraction of SiC_p reaches certain amount as illustrated in Figure 2.10, the wear loss is completely zero. This has been confirmed by Miyajima and Iwai in their microstructure study. They found that the worn surface of MMCs with higher volume of SiC_p exhibits smooth flat surface without large groove. Comparison on effectiveness of various reinforcement also done by Miyajima and Iwai. They suggested that, particle reinforcement has advantages to prevent wear loss because of its shape and diameter which is largest in this experiment.

Similar results were also obtained for steady state condition. However, there is an exception for fiber reinforced MMC. Wear loss of fiber reinforced MMC decreases with the increase of volume fraction and in certain value, it will increase again (Figure 2.11). Miyajima and Iwai have also compared the results from this experiment with other results from his literature review. From that, they concluded that particle reinforcements was excellent in preventing wear loss compared to other types of reinforcements. Type of reinforcement used has substantial influence on the properties of the composites.

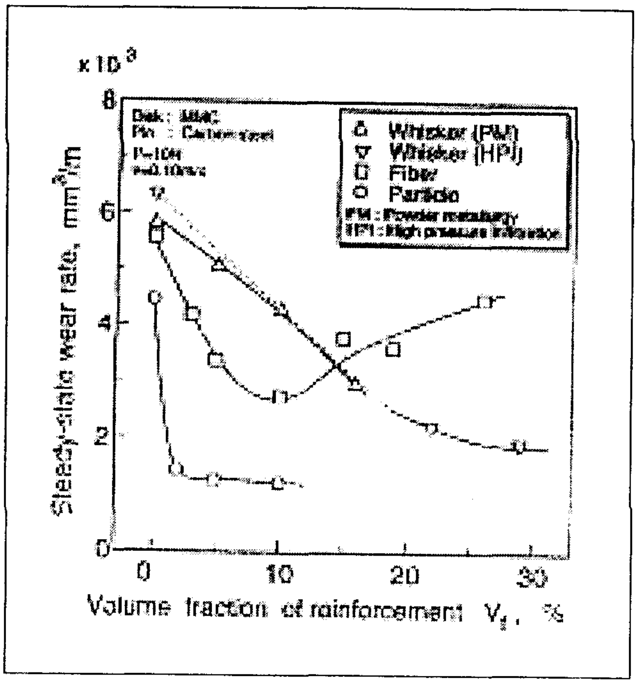
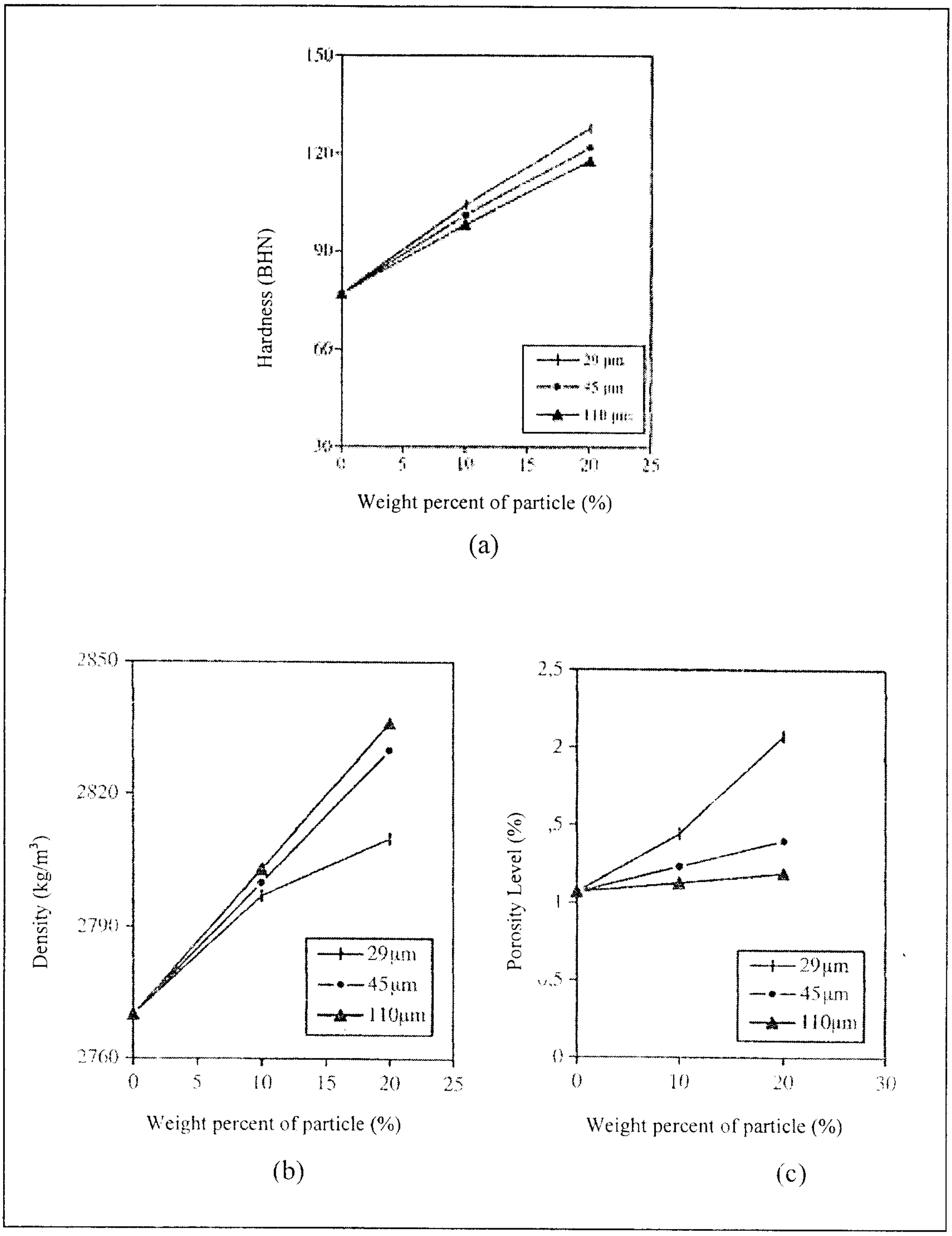


Figure 2.11:Wear Rates of MMCs (Disk Specimen) in Steady State Wear Regime as Function of Volume Fraction,V_f (Miyajima and Iwai, 2003)

2.7.4 Study on Production and Properties of SiCp-Reinforced Aluminium Alloy Composites.

In this study, Sahin (2003), intended to produce Al-MMCs by molten metal mixing and squeeze casting. The purpose of his study was to find out the influence of particle sizes and volume fraction of SiC on mechanical properties (density, hardness and porosity) of Al-MMCs. Aspects of tool wear was also investigated by him but will not to be discussed here.

Combinations of specimens used in this study are Al-2014 with: 10wt.% SiCp (29μm particles); 10wt.% SiCp (45μm particles), 10wt.% SiCp (110μm particles); 20wt.% SiCp (29μm particles); 20wt. SiCp (45μm particles); 20wt.% SiCp (110μm particles).



Figures 2.12: a) Variation of Hardness with Volume Fraction Particle; b) Variation of Density with Volume Fraction Particle ;c) Variation Of Porosity with Volume Fraction Particle (Sahin, 2003)

The results indicate composite with smaller particles size exhibit higher value of hardness and porosity level. As for density, the other way occurred, density increases with larger or bigger particles size. Besides from particles sizes, the volume fraction of particle also tends to influence mechanical properties of AL-MMC as seen from Figure 2.12.

2.7.5 Study on Casting of Aluminium Alloy Based Metal Matrix Composite

In this study, Hameedullah *et. al* (2004), investigated the density, hardness, fracture toughness and wear resistance of Al-MMC produced by stir casting method. For preparing the specimen, metallic mould is used. This experiment was planned according to 2x3x3 factorial design as illustrated in Table 2.7.

Table 2.7: Treatment Combinations According 2x3x3 (Hameedullah et al., 2004)

Pouring Temperature (^{o}C)		750			800			850		
Percentage of SiC		5	10	15	5	10	15	5	10	15
Particle Size	5 micron	---	-0-	-+-	0--	00-	0+-	+--	+0-	++-
	53 micron	--+	-0+	-++	0-+	00+	0++	+-+	+0+	+++

- Low level; 0 Medium level; + High level

From this study, it is found that the wear resistance, toughness, and density of aluminium metal matrix composite increased with the increasing of percentage of silicon carbide particulates. Size of SiC_p also contributes some effect the Al-MMC properties. Coarser SiC_p will increase the wear resistance and toughness of Al-MMC while slighty lowers the density and hardness of Al-MMC. He also concluded that $800^{o}C$ is the optimum pouring temperature based on the trend of variation or changes of the wear resistance, toughness and hardness results.

Besides from this study, the almost similar experiment was also done but Jananee. However she includes the investigation of optimum level of clay and water content in preparing sand mould and also microstructures in her study. These will not be discussed here. Emphasized will be given to the influence of particle size of reinforcement, stirring time and pouring temperature to the wear, fracture toughness and hardness of Al-MMC. 2^3 factorial design was used in this experiment.

Variables factors considered in this experimental and treatment combination diagram are depicted in Table 2.10 and Table 2.11 respectively.

Table 2.8: Variable Factors (Jananee, 2004)

	Factor	Description	Lower Level	Higher Level
1	A	Pouring Temperature	850°C	900°C
2	B	Particle size of SiC	50 micron	106 micron
3	C	Stirring Time	1 min	5 min

Table 2.9: Treatment Combination Diagram For 2x2x2 Factorial Design (Jananee, 2004)

Exp No	**Factor**			**Specimen Combination**
	A *(Stir)*	**B** *(Size)*	**C** *(Temp)*	
1	0	0	0	$A_0B_0C_0$
2	1	0	0	$A_1b_0C_0$
3	0	1	0	$A_0B_1C_0$
4	1	1	0	$A_1B_1C_0$
5	0	0	1	$A_0B_0C_1$
6	1	0	1	$A_1B_0C_1$
7	0	1	1	$A_0B_1C_1$
8	1	1	1	$A_1 B_1C_1$

In this study, it is found that the hardness and toughness of Al-MMC will decrease with the increasing of SiCp size. However the wear resistance tends to increase. The pouring temperature also has influence on the properties of Al-MMC. Longer stirring time will increases hardness, fracture toughness but lower wear resistance of Al-MMC. Apart from that, interaction between particle size and pouring temperature exhibit significant effect on wear resistance of Al-MMC. For other testing, no significant combination was found.

2.8 Comparison of Studies

Table 2.10: Comparison of the Studies (Multiple Reference)

Researcher(s) / Reference	Composites/ materials	Manufacturing Process	Factors Considered	Types of mechanical Testing	Mechanical Properties Result (Conclusion)
Garcia, *et.al* (1995)	A357+SiC_g,A339+SiC_g, A339SiC_p, AA6061+SiC_g, AA6061+Al_2O_3, Cast iron disc and A357 disc	Compocasting	a) Particle size of SiC (G400, G500, G600) b)Volume Fraction of SiC (0, 10, 13, 15, 20%)	Abrasive wear and hardness test * Metallography observation is also done in this study	a) Wear resistance of composites increases as the volume fraction or the particles size of reinforcements increase. b) Relative wear rate of A339 and A357 composites increases with the inverse of their relative hardness. c) Wear resistance of Al composites and gray cast iron are similar
Bindumadhavan, *et.al* (2000)	A356+SiC_p	Stir Casting	a) Particle size and volume fraction of SiC_p b)2 types of combination considered: single particle size (SPS) and Double particle size (DPS)	Dry sliding wear, hardness and impact * Metallography observation also done in this study	a) Wear resistance of composites increases as the volume fraction of reinforcement increase. b) Macrohardness of SPS (47μm) composites increase as volume fraction of SiC_p increase c) DPS (47μm+120μ) composites exhibit lower wear loss compared to SPS (47μm) composite for the same volume of SiC_p d) Composites with larger SiC_p were found have higher impact energy
Miyajima and Iwai (2003	Al2024+SiC whisker, Al2024+SiC particle and ADC12+Al_2O_3 fiber	Powder metallurgy and high pressure (whisker), die casting technique (fiber) and powder metallurgy (particle)	a) Types and volume fraction of reinforcement	Dry sliding wear	a)Type of reinforcement used also has substantial influence on the wear resistance of the composites. b) Wear resistance of composites increases as the volume fraction of reinforcement increase. c) Particle reinforcement is the best in improving wear resistance of composites

Sahin (2003)	Al-2014 alloy + SiC_p	Molten metal mixing and squeeze	a) Particles size of SiC (29,45 and 110μm) b) Volume fraction of SiC_p (10 and 20wt%) * Tool life of cutting tools when machining composites is also included in this study but will not discussed here.	Density, hardness, porosity level	a) Composites with smaller particles size exhibits higher value of hardness and porosity level b) Density increases when size of particles and weight percentage of SiC increase. c) Porosity level and hardness increase when weight percentage of SiC increase.
Hameedullah (2004)	Al+ SiC_p	Stir Casting (metallic mould)	a) Particles size of SiC (5μm and 53μm) b) Volume fraction of SiC_p (5,10 and 20 wt%) c) Pouring temperature (750°C, 800°C and 850°C)	Density, hardness, toughness and wear resistance	a) Wear resistance, toughness, and density of aluminium metal matrix composite increase with the increasing of percentage of silicon carbide particulates b) Coarser SiC_p will increase the wear resistance and toughness of Al-MMC while slighty lower the density and hardness of Al-MMC
Jananee, (2004)	Al+ SiC_p	Stir Casting (Sand Mould)	a) Stirring time (1 and 5 minutes) b) Particle size of SiC (50 and 106 μm) c) Pouring temperature (850°C and 900°C) * Investigation on optimum content of clay and water contents also included in this experiment but not discuss here	Wear, fracture toughness and hardness	a) Hardness and toughness of Al-MMC will decrease with the increasing of SiCp size. However wear resistance tends to increase b)Longer stirring time will increases hardness, fracture toughness but lower wear resistance of Al-MMC. c) Interaction between particle size and pouring temperature exhibit significant effect on wear resistance of Al-MMC

2.9 Gray Cast Iron and Al-MMC for Automotive Components (Disc Brake)

Gray cast iron has played a vital role in automotive applications. This material is chosen because of its high wear resistance, high strength, hardness and low cost. Disc brake, for instance is produced from gray cast iron. The classification of gray cast iron and its applications are depicted in Table 2.13. From Table 2.11, it is noted that, gray cast iron with grade G2500, G2500a, G3000, G3500, G3500b and G3500C are suitable for brake drum application. The properties of gray cast iron are depicted in Table 2.12.

Table 2.11: Typical Applications of Gray Cast Iron for Automotive Castings (ASM Metal Handbook, 1995)

Grade	Applications
G1800	Miscellaneous soft iron castings (as cast or annealed) in which strength is not of primary consideration due to heat.
G2500	Small cylinder blocks, cylinder heads, air cooled cylinders, pistons, clutch plates, oil pump bodies, transmission cases, gear boxes, clutch housings and light- duty brake drums.
G2500a	Brake drums and clutch plates for moderate service requirements where high carbon iron is desired to minimize heat checking
G3000	Automobile and diesel cylinder blocks, cylinder heads, flywheels, differential carrier castings, pistons, medium-duty brake drums and clutch plates.
G3500	Diesel engine blocks, truck and tractor cylinder blocks and heads, heavy flywheels, tractor transmission cases and heavy gear boxes
G3500b	Brake drums and clutch plates for heavy duty service where both resistance to heat checking and higher strength are definite requirements
G3500C	Brake drums for extra heavy duty service
G4000	Diesel engine castings, liners, cylinders and pistons.
G4000d	Camshafts

Table 2.12 : Gray Cast Iron and its Properties (http://www.matweb.com/search/SearchProperty.asp)

Num	Types of Gray Cast Iron	Density (g/cm^3)	Vickers Hardness (HV)
1	Gray Cast Iron	7.15	246
2	SAE J431 automotive gray cast iron, SAE grade G1800		195
3	SAE J431 automotive gray cast iron, SAE grade G2500		209
4	SAE J431 automotive gray cast iron, SAE grade G3000		225
5	SAE J431 automotive gray cast iron, SAE grade G3500		243
7	SAE J431 automotive gray cast iron, SAE grade G4000		256

However, the rapid development in science of material has lead to introduction of new materials for brake drum. There are particle reinforced Al-MMC and carbon fibre reinforced carbon. Only Al-MMC will be discussed in this experimental study. The advantage of Al-MMC is lower density (weight) compared with gray cast iron. Others properties such as wear resistance, tensile strength and elastic modulus are similar or even better than gray cast iron.

One of the limiting factors for the use of Al-MMC in brake application is its low melting temperature compared to gray cast iron. Therefore Al-MMC is sometimes used on the rear axles of automobiles because the energy dissipation requirements are not as severe compared with front axles (Blau, 2001). As we all know, drum brake is usually used in the rear axles of the vehicle. In addition, industry experts say that the drum maximum temperature should not exceed 399°C to 427°C (Grimes, 1999). Therefore Al-MMC is still suitable for light or medium duty brake drum. The melting temperature of Aluminium LM6 used in this experimental study is 650-760°C (ASM Metals Handbook, 1995).

Breuer (2003) in his article entitled "New Material Technologies for Brakes" mentioned that the application of Al-MMC in disc brake (front axles) is possible for small and light car (For instance,Lotus Elise). Typical Al-MMC used in brake application (brake drum) is Duralcan. Duralcan is a family of particulate Al-MMC reinforced with particulate ceramic produced by Alcan Aluminium Ltd. This material is usually used in automotive components such as brake drum, brake disc and gear box components (http://mmc-assess.tuwien.ac.at/index1.htm). Table 2.13 depicts the properties of Duralcan composites

Table 2.13:Properties of Duralcan composites- ambient temperature (http://mmc-assess.tuwien.ac.at/index1.htm).

Matrix	Aluminium Cast Alloy-A359	
Reinforcement (Sizes)	Irregularly shaped SiC particles	
Reinforcement (Volume)	10% and 20 %	
Production Route	Gravity Casting	
Type	**F3S.10S-T6**	**F3S.20S-T6**
Ultimate Strength (MPa)	338	359
Yield Strength (MPa)	303	338
Elongation (%)	1.2	0.4
Elastic Modulus (GPa)	86.2	98.6
Rockwell Hardness (HRB)	73	77
Density (g/cm^3)	2.71	2.77

The comparison of mechanical properties between Al-MMC (Duralcan and gray cast iron is depicted in Table 2.14.

Table 2.14: Comparison of Mechanical Properties Between Al-MMC (Duralcan) and Gray Cast Iron (Blau, 2001)

Property	Unit	Al-MMC Type F3S20S-T61 (Duralcan)	Al-MMC Type F3D20S-T5 (Duralcan)	Gray Cast Iron Grade 30/35
Elastic Modulus	GPa	98.5950	113.7634	89.6318 - 118.5898
Yield Strength	MPa	337.8431	393.0011	213.7375 - 268.8955
Density	g/cm^3	2.7652	2.8206	7.1137
Thermal Conductivity	W/m.K	181.7271	147.9778	47.2491
Specific Heat	kJ/kg.K	0.8374	0.8290	0.4019
Thermal Expansion Coefficient	$10^6/^0F$	9.7	9.4	6.8

2.10 Design of Experiments

There are many types of methods for planning and conducting experiment, and analyzing data from the experiments. Some of the methods require the experiment to be run repetitively in order to determine the average results from the repetitive experiments. The average value represents the overall results of the experiment. However, this type of method only considers one experimental variable (factor) in the same experiment. It is called single factor experiment. Interaction, combinations and joint effects of various variables could not be analyzed or determined by this method. Experiments should be repeated if the experimenter wishes to identify the effect of other factors. This is not suitable for industrial use or research work where the cost of testing and materials are relatively high.

There are many approaches to the planning of experimental conditions. These are one-factor-at-a-time experiments, full factorial design, fractional orthogonal design and Taguchi's Robust Parametric Design.

a) One-Factor-at-a-Time Experiments

One-factor-at-a-time experiments are experiments in which the researcher simply changes one x at a time to determine its effect on the y. This are simple to design and analyze, but they have shortcomings. First, they provide no information on interactions between factors. Second, experimenters may run out of time and/or money before they have enough information to make an informed decision.

Table 2.15: One-factor-at-a-Time Experiments

Description	X_1	X_2	X_3	X_4	X_5	X_6	X_7	y
Standard	-	-	-	-	-	-	-	
Trial 2	+	-	-	-	-	-	-	
Trial 3	-	+	-	-	-	-	-	
Trial 4	-	-	+	-	-	-	-	
Trial 5	-	-	-	+	-	-	-	
Trial 6	-	-	-	-	+	-	-	
Trial 7	-	-	-	-	-	+	-	
Trial 8	-	-	-	-	-	-	+	

b) Full factorial design

Multiple factors (two or more) can be designed into experiments with what is termed a full factorial design. In complete full factorial arrangement, all possible treatment combinations (of factor levels) are observed and their responses recorded. In a full factorial design, two, three, or more levels of the selected factors will be of interest. When two levels of each factor are studied, the arrangement is termed a 2^f, where f represents the number of factors. A 2^f will require 2^f factor level treatment combinations. For example, 2^3 we have 2x2x2 = 8 treatment combinations. Table 2.16 shows the 2^3 treatment combinations table.

Table 2.16 : 2^3 treatment combinations

Notation	A	B	C	AB	AC	BC	ABC
(1)	-	-	-	+	+	+	-
a	+	-	-	-	-	+	+
b	-	+	-	-	+	-	+
ab	+	+	-	+	-	-	-
c	-	-	+	+	-	-	+
ac	+	-	+	-	+	-	-
bc	-	+	+	-	-	+	-
abc	+	+	+	+	+	+	+

c) Fractional factorial designs

When four or more factors are to be considered, it often becomes costly or impossible to simultaneously run all possible treatment combinations. For example, four factors each with two levels involve 16 treatment combinations; five factors each with two levels involve 32 treatment combinations; and seven factors each with two levels involve 128 treatment combinations. Thus, as the number of factors in experiment increases, there needs to be a rational way of choosing a subset of the treatment combinations so that an experiment with meaningful results can be undertaken. One way to do this is through the use of a fractional factorial design.

In a fractional factorial design, only a subset of all possible treatment combinations is used. The more factors involved, the more treatment combinations to consider. One approach is to choose the treatment combinations so that each main effect can be independently estimated without being confused or confounded with any estimate of the two factor interactions. When a main effect or an interaction is confounded, its effect cannot be isolated from the main effect of some other factor or interaction.

d) Taguchi's Robust Parametric Design

Taguchi's approach to parameter design provides the design engineer with a systematic and efficient method for determining near optimum design parameters for performance and cost (Kackar, 1985; Phadke, 1989; Taguchi 1986). The objective is to select the best combination of control parameters so that the product or process is most robust with respect to noise factors. The Taguchi method utilizes orthogonal arrays from design of experiments theory to study a large number of variables with a small number of experiments. Using orthogonal arrays significantly reduces the number of experimental configurations to be studied. Furthermore, the conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings (Phadke, 1989). Orthogonal arrays are not unique to Taguchi. They were discovered considerably earlier (Bendell, 1988). However, Taguchi has simplified their use by providing tabulated sets of standard orthogonal arrays and corresponding linear graphs to fit specific projects (Taguchi and Konishi, 1987). A typical tabulation is shown in Table 2.17.

Table 2.17: L_9 (3^4) Orthogonal Array

	A	B	C	D
1	0	0	0	0
2	0	1	1	1
3	0	2	2	2
4	1	0	1	2
5	1	1	2	0
6	1	2	0	1
7	2	0	2	1
8	2	1	0	2
9	2	2	1	0

In this array, the columns are mutually orthogonal. That is, for any pair of columns, all combinations of factor levels occur; and they occur an equal number of times. Here there are four parameters A, B, C, and D, each at three levels. This is called an L_9 design, with the 9 indicating the nine rows, configurations, or prototypes to be tested. Specific test characteristics for each experimental evaluation are identified in the associated row of the table. Thus, L_9 means that nine experiments are to be carried out to study four variables at three levels. The number of columns of an array represents the maximum number of parameters that can be studied using that array. Note that this design reduces 81 (3^4) configurations to 9 experimental evaluations. There are greater savings in testing for the larger arrays. For example, using an L_{27} array, 13 parameters can be studied at 3 levels by running only 27 experiments instead of 1,594,323 (3^{13}). The Taguchi method can reduce research and development costs by improving the efficiency of generating information needed to design systems that are insensitive to usage conditions, manufacturing variation, and deterioration of parts. As a result, development time can be shortened significantly; and important design parameters affecting operation, performance, and cost can be identified. Furthermore, the optimum choice of parameters can result in wider tolerances so that low cost components and production processes can be used. Thus, manufacturing and operations costs can also be greatly reduced.

2.10.1 Steps for Designing Experiments

a) *Define the objectives*

The objective of the experiment must be clearly and specifically defined. It is because the objectives will represent the goals of the study. In this experimental study, the influence of particle sizes of SiC on mechanical properties of Al-Cu-SiC_p will be the main objectives.

b) *Identify choice of control factors, levels and noise factors*

The control factors refer to the controlled experimental parameters that could affect the performance of the process. In this experimental study, the control factors are those parameters which will affect the mechanical and physical properties of Al-Cu-SiC_p. The selected factors for this experiment are among the most influential and critical to the properties of Al-Cu-SiC_p. The selected control factors are particles sizes of SiC, weight percentage of SiC, pouring temperature and time of stirring. Other factors (besides from particle sizes of SiC) are also included because it also influence the properties of Al-Cu-SiC_p. Moreover in real industry, the output of certain process is influenced by multiple factors and not only by single factor. After selecting the control factors, the level for each factor must be identified. Levels of the factors refer to its varied conditions during the experiment.

For noise factors, it is the uncontrollable factor that will also affect the experiment results.

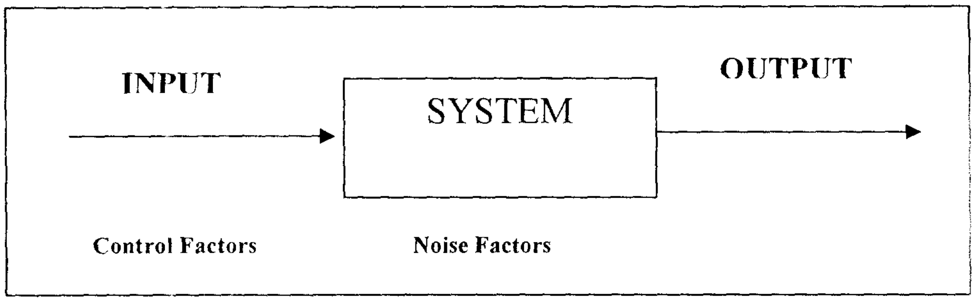


Figure 2.13: Factor –Characteristic Relation Diagram

c) Selection of Orthogonal Array

Orthogonal Array is a set of table where listed number of run and variation of factor considered. Each of the table is fixed and its reliability tested by the expert. The selection of orthogonal array is based on number of control factors and their levels. In this experimental study, three-level factors are considered. L_9 Orthogonal Arrays is chosen because it suits the number and level of factors in this experimental study. The number 9 represents the number of combinations of process parameters that are used to investigate the effect of parameters on the response variables. With orthogonal arrays, reliable and meaningful conclusion can be translated from minimum number of data or experiments. The L_9 orthogonal array is depicted in Table 2.18.

Table 2.18: Layout of Taguchi's Robust Parametric Design

Experiment Number	Inner array				Outer array		SN
	Control Factor Assignment				Response number		
	A	B	C	D	y_{i1}	y_{i2}	
1	0	0	0	0	y_{11}	y_{12}	SN_1
2	0	1	1	1	y_{21}	y_{22}	SN_2
3	0	2	2	2	y_{31}	y_{32}	SN_3
4	1	0	1	2	y_{41}	y_{42}	SN_4
5	1	1	2	0	y_{51}	y_{52}	SN_5
6	1	2	0	1	y_{61}	y_{62}	SN_6
7	2	0	2	1	y_{71}	y_{72}	SN_7
8	2	1	0	2	y_{81}	y_{82}	SN_8
9	2	2	1	0	y_{91}	y_{92}	SN_9

The number 0, 1 and 2 represent the level for each of the factor. In this experimental study, signal to noise (SN) consolidates the repetitions values for each experiment's run into single value. It will reflect the amount of variation presents for each of the experiment's run caused by noise factors

d) *Selection of the response variables*

Only response variables which provide direct and useful information on the objective of the experimental study will be selected. As stated earlier, the mechanical and physical properties of Al-Cu-SiC_p are the main concern in this study. Therefore, it should be the response variables in this experiment. In this experimental study, only 4 types of testing were chosen. These are: hardness, wear, density and compression tests.

e) *Conduct the experiment*

The specimens prepared are subjected to wear, hardness, density, compressive strength and flexural behaviour test. This step must performed properly to ensure experimental work done as planned or scheduled.

f) *Statistical analysis of the data*

The statistical analysis (Pareto-ANOVA) is done manually. Significant factor that influences the mechanical and physical properties of Al-Cu-SiC_p can be determined. This method is also capable to find out the optimum combination for each type of testing.

g) *Conclusion and recommendations*

From the analyzed data, we can determine the significant effect to the new developed material. Lastly, recommendation also can be drawn out from the analysis.

2.11 Summary of Literature Studies

Based on the study of the literature reviews, it can be concluded the mechanical properties of Al-MMC can be tailored. By controlling the size of particles, amount of particles, Al-MMC with desired properties can be produced. All of these factors have significant effect on the properties of Al-MMC. Therefore a better understanding and knowledge on relationship between these factors and mechanical properties of Al-MMC will help us to enhance and boost the usage of this material in industry. For instance, Al-Cu-SiC_p MMC may be applied in brake system of automotive industry. By applying Al-Cu-SiC_p MMC in brake applications, it will offer advantages especially in reducing the weight of vehicle. In this work, Al- 4.5 % Cu alloy composite matrix reinforced with SiC_p will be produced by stir casting process. The ceramic (SiC_p) particle size, pouring temperature, ceramic powder (SiC_p) weight percentage and stirring time will be varied. Parameter design (L_9 Orthogonal Array) will be used for planning the experiment and Pareto ANOVA will be used to determine the significant and optimum input variables for hardness, density, wear resistance, compressive strength and flexural behaviour.