POROSITY STUDY AND EFFECTS ON MECHANICAL PROPERTIES OF DISCONTINUOUS REINFORCED METAL MATRIX COMPOSITE (DRMMC)

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SYARIFAH NUR AQIDA BINTI SYED AHMAD

A thesis submitted in fulfilment of the requirements for the award of the Degree of
Master of Engineering (Mechanical)

Kolej Universiti Teknologi Tun Hussein Onn

FEBRUARY 2004

"I declare that this thesis entitled "*Porosity Study and Effects on the mechanical Properties of Discontinuous Reinforced Metal Matrix Composite (DRMMC)*" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree."

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ABSTRACT

The effects of porosity on mechanical properties of cast discontinuous reinforced metal matrix composite (DRMMC) were investigated. Hence, a casting rig was fabricated to produce DRMMCs via conventional and modified stir casting method. The modified stir casting method performed pre-heating of reinforcement particles during matrix alloy melting. Silicon carbide particle reinforced aluminium alloy composites were produced with three different stirring speeds: 100, 200 and 500rpm. Cast DRMMCs were evaluated in as-cast condition for microstructure analysis, porosity and density measurement and mechanical testing. The mechanical properties of cast DRMMC were determined from tensile and fatigue tests conducted at room temperature. Tensile tests were referred to ASTM B557 standard while the axial fatigue test (ASTM E466) was conducted at stress ratio (R) of -1. A finite element method (FEM) analysis was carried out using Solidworks 2003 software. It was found that the major causes of porosity occurrence in cast DRMMC were clustered silicon carbide particles, gas entrapment and solidification shrinkage. From porosity measurement, conventionally stir cast DRMMCs contained higher porosity compared to the modified stir cast DRMMCs. The least content of porosity evaluated is at 0.09% in modified stir cast DRMMC, while the highest is at 12.45% in conventionally stir cast DRMMC. Fatigue strength (at 1×10^7 cycles) of cast DRMMCs at 5, 10, and 15% reinforcing SiC particle were 129.7, 141.5 and 157.3 MPa respectively. Based on the FEM analysis, porosity in conventionally stir cast DRMMC promotes higher von Mises stress as much as 40.2 MPa compared to 12.6 MPa in modified stir cast DRMMC. The porosity contents increased with increasing silicon carbide particles. Higher stirring speed tended to entrap more gas during mixing, whereas a lower stirring speed was ineffective to disperse SiC particles and results in clustering. Increasing porosity content in cast DRMMC had decreased the density and tensile properties of DRMMC as depicted by the FEM analysis. Though, fatigue strength increased as a result of existing constraints in form of porosity.

ABSTRAK

Kesan-kesan keliangan ke atas sifat mekanik tuangan komposit matriks logam bertetulang partikel (KMLBP) telah dikaji. Satu *'casting rig'* telah direkabentuk untuk menghasilkan KMLBP melalui kaedah tuangan kacau biasa dan tuangan kacau terubahsuai. Di dalam kaedah tuangan kacau terubahsuai, proses pra-pemanasan terhadap partikel telah dilakukan semasa peleburan aloi matriks. Komposit aloi aluminium bertetulang partikel silikon karbida dihasilkan dengan tiga kelajuan pengacauan yang berbeza iaitu 100, 200 dan 500 ppm. Tuangan KMLBP dinilai untuk analisis mikrostruktur, pengukuran ketumpatan dan pengukuran keliangan serta ujian mekanikal. Sifat mekanik tuangan KMLBP ditentukan daripada ujian tegangan dan ujian lesu yang dijalankan pada suhu bilik. Ujian tegangan ini merujuk kepada piawaian ASTM B557. Manakala ujian lesu yang dilakukan pada nisbah tegasan (R), -1 pula merujuk kepada piawaian ASTM E466. Analisis kaedah unsur terhingga (KUT) dilakukan menggunakan perisian *Solidworks 2003*. Daripada kajian, didapati bahawa punca utama pembentukan keliangan di dalam tuangan KMLBP adalah partikel silikon karbida yang berkelompok, gas yang terperangkap dan pengecutan semasa proses pemejalan. Melalui pengukuran keliangan, KMLBP yang dihasilkan melalui tuangan kacau biasa mengandungi peratusan keliangan yang lebih tinggi berbanding KMLBP yang dihasilkan melalui tuangan kacau terubahsuai. Kandungan keliangan minimum yang diperolehi adalah 0.09% di dalam KMLBP tuangan kacau terubahsuai, manakala kandungan yang tertinggi pula didapati di dalam KMLBP tuangan kacau biasa iaitu 12.45%. Kekuatan lesu (pada $1\text{x}10^7$ kitar) tuangan KMLBP dengan kandungan partikel silikon karbida 5%, 10% dan 15% masing-masing ialah 129.7 MPa, 141.5 MPa dan 157.3 MPa. Berdasarkan kepada analisis KUT, keliangan di dalam KMLBP tuangan kacau biasa memberikan tegasan von Mises yang lebih tinggi iaitu 40.2 MPa berbanding 12.6 MPa di dalam KMLBP tuangan kacau terubahsuai. Kandungan keliangan juga meningkat dengan pertambahan kandungan partikel silikon karbida. Halaju pengacauan

yang lebih tinggi cenderung untuk memerangkap lebih banyak gas manakala halaju pengacauan yang lebih rendah pula kurang berkesan untuk menyerakkan partikel silikon karbida dengan lebih seragam. Peningkatan kandungan keliangan dalam tuangan KMLBP merendahkan ketumpatan dan sifat tegangan KMLBP. Namun, kekuatan lesu meningkat akibat kewujudan kekangan yang dihasilkan oleh keliangan.

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II LITERATURE REVIEW AND THEORETICAL BACKGROUND

III RESEARCH METHODOLOGY AND PROCEDURES

IV RESULTS AND DISCUSSION

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LIST OF SYMBOLS

A - surface area
A - length of reduced section
AA - roughness average (Ra)
d - diameter
E - elastic modulus
G - gauge length
G - Grip cross-sectional area
Hz - Hertz
L - test section length
Nf - cycles to failure
Pa - Pascal
R - stress ratio
R - radius of fillet
R – radius of curvature
R^2 - regression factor
s - mean aspect ratio
T - thickness
V_f - volume fraction
V_m - volume fraction of matrix
V_p - volume fraction of particle
V_v - volume fraction of void
σ_Y - yield strength
σ_{UTS} - ultimate tensile strength
σ_C^Y - yield strength of composite

σ_m^Y - yield strength of matrix alloy

σ_C^{UTS} - ultimate tensile strength of composite

σ_m^{UTS} - ultimate tensile strength of matrix alloy

σ_p^{UTS} - ultimate tensile strength of reinforcing particle

υ - Poisson's ratio

$\varnothing$ - diameter

LIST OF ABBREVIATIONS

A356 - Aluminium silicon alloy

Al - Aluminium

Al_2O_3 - Aluminium Oxide

ASTM - American Society for Testing and Materials

B - Boron

C - Carbon

CMC - Ceramic Matrix Composite

CNC - Computer Numerical Control

CO - Carbon monoxide

DC - Direct current

DRMMC - Discontinuous Reinforced Metal Matrix Composite

EDM - Electrical Discharge Machining

FEM - Finite Element Method

FOS - Factor of Safety

H_2 - Hydrogen gas

H_2O - Water

MMC - Metal Matrix Composite

O_2 - Oxygen gas

PMC - Polymer Matrix Composite

RMS - Root mean square

rpm - Revolve per minute

SEM - Scanning Electron Microscopy

SiC_p - Silicon Carbide particles

Si_3N_4 - Silicon Nitride

SiO_2 - Silicon Oxide

TiC - Titanium Carbide

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CHAPTER I

INTRODUCTION

Metal matrix composites (MMCs) were initially transpired as early as 1960s where aluminium or copper were commonly used as matrix materials reinforced with 30-70% of continuous tungsten or boron fibres. Expansion of MMCs production in 1980s had deliberately led to the development of discontinuously reinforced metal matrix composites (Clyne, 1996). Generally, metal matrix composite is a material consisting of metal alloys reinforced with continuous fibres, or whiskers and particulates. Various forms of reinforcement are shown in Figure 1.1, ranging in diameter from a few micrometers to nearly 300μm. B, Al_2O_3, C, SiC, and steel wires were among the greatest interest of fibres, while among the whiskers and particulates were SiC, Si_3N_4, Al_2O_3 and TiC which were normally ceramic material. In order to combine the desirable attributes of metals and ceramics, MMCs were designed. They have many advantages, which include high strength, toughness at elevated temperature, low density, and higher stiffness and mechanical strength compared to matrix alloys. Some applications of MMC are shown in Table 1.1.

Various processing methods established along with MMC evolution were classified into solid state and liquid state processing. Recent studies of MMC were particularly claimed on the development of discontinuous reinforced MMC (DRMMC). Consequently, the particle reinforced MMC is developing into the most important of metal matrix composites. It was essentially focused on aluminium based matrices reinforced with SiC, or Al_2O_3 particles. Hence, five selected processing routes for fabricating DRMMC reviewed were stir casting, squeeze infiltration, powder metallurgy, spray casting and Lanxide technique (Hashim et. al, 1999). Apparently, an attractive processing route of DRMMC was defined for its economic approach, large production size and undamaged reinforcement material. Recognizing the advatages of stir casting method in fabricating DRMMCs, this method had been employed in many studies.

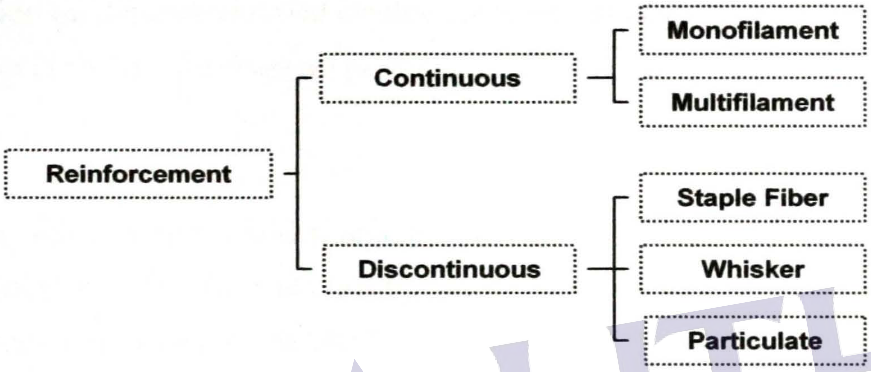

Figure 1.1: Forms of reinforcement

Table 1.1: Some applications of MMCs

Industrial sector	Application
Aerospace	Struts, antennae, microwave packaging, space shuttle.
Automotive	Piston crowns, engine block, braking components, drive shafts.
Electronic	Superconductors, contacts, filaments, electrodes, electronic packaging.
Sport	Bicycle frame, golf club shaft, tennis racket, baseball bats.

1.1 Research Background

The shaping of DRMMC material future in various industries in fact depends on attractive yet economic manufacturing technology. Though expensive methods produced excellent properties of DRMMC, the bargain of substituting former material to DRMMC would be unworthy. Several reviews cited on the occurring porosity in casting tend to affect the mechanical properties. Nonetheless, modification on the conventional casting route was studied to consider the effects of porosity on DRMMC mechanical properties.

The stir casting method is among widely practiced processing routes to produce DRMMC. Mechanical stirring employed is purposely relevant for mixing the two main substances of DRMMC; the matrix alloy and reinforcement particles or whiskers. A sound casting would indeed require a uniform distribution of reinforcement material, minimum porosity content and good wettability between matrix alloy and reinforcement material. Confronted with the porosity problem in DRMMC casting, a modified stir casting was established to minimize the porosity content. Wettability of the two main substances in DRMMC was resolved through heat treatment of reinforcement particles before casting whereas a uniform distribution of particles in matrix alloy was acquired via mechanical stirring. In spite of this, there were several factors leading to porosity formation in cast DRMMC, which concerned the stirring speed and volume fraction of reinforcing material.

1.2 Research Hypothesis

Among the factors influencing the porosity formation are the casting route (Hassan & Gupta, 2002, Hashim et. al, 1999, McCoy et. al, 1988 and Ghosh & Ray, 1987), casting process parameters (Moustafa, 1997 and Ghosh & Ray, 1988), and the volume fraction of reinforcement material in DRMMC (Hashim, 1999 and Ramani et. al, 1993).

Porosity formation is caused by gas entrapment during vigorous stirring, air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles, water vapour (H_2O) on the surface of the particles, hydrogen evolution and shrinkage during solidification (Hashim, 1999, Hashim et. al, 1999, Moustafa, 1997, Ejiofor & Reddy, 1997 and Kennedy et. al, 1995).

Modified stir casting route enable pre-heating of reinforcement material during heating process, before the mixing which helps to vanish the air envelope among particles as well as the gas trapped and water vapour due to high humidity (Hassan & Gupta, 2002, Hashim, 1999, and McCoy et. al, 1988). Obviously, conventional stir casting route increases the probability of gas entrapment and water vapour entrance by adding the reinforcement particles into the matrix melt from the top (Hashim et. al, 1999).

From previous review, porosity was marked as a defect, which is associated with degradation of material strength. The significant mechanical and physical properties affected by porosity formation were the yield stress, tensile strength, elasticity, fatigue strength and density. Porosity tends to decrease the mechanical properties of DRMMC (Jung et. al, 2000, Chen et. al, 1997, Murali et. al, 1997, Clyne, 1996 and Skolianos, 1995). Previous work associated the formation and growth of voids (porosity) with decreasing yield strength of composites (Chen et. al, 1997), and reduction of the total life time (Murali et. al, 1997). Eliminating porosity is impossible as previous works revealed volume fraction of microporosity present was up to 7% (Whitehouse, 2000).

1.3 Importance of The Study

Reviewing previous works of Hashim (1999) and Kennedy et. al (1995), porosity is among the four occurring problems in stir casting method. Porosity surely exists in stir cast DRMMC as the foregoing processing method required mechanical mixing to distribute the reinforcing material. Though, stir casting method is still preferred for fabricating DRMMC in the industry sector for its low cost processing. Excessive volume fraction of porosity (>1%) was reviewed to affect the physical and mechanical properties of cast DRMMC severely. Apparently, formation of porosity reduces the density of cast DRMMC. Besides, decreasing of mechanical properties of cast DRMMC due to porosity formation had consumed the benefit of DRMMC properties in replacing ferrous metals application. Recent studies on producing DRMMC via stir casting method had convinced a further research on defeating the porosity content in stir cast DRMMC which is presented in this study. The present study exhibited modification of stir casting method to clarify the porosity as a treatable defect. In viewing this, it is significant to study the factor of porosity formation in cast DRMMC and the affected mechanical properties.

1.4 Research Objective

The objective of this research is to study the porosity formation and its effects on the physical and mechanical properties of cast DRMMC fabricated via stir casting processing method. Variables concerned were the processing method, stirring speed and volume fraction of reinforcing particles.

1.5 Scope of Study

In order to meet the research objective, the scopes of study are:

i. Design and fabricate a bottom pouring stir casting rig.

ii. Produce cast DRMMC ingots (with diameter of 20mm) via conventional and modified stir casting method at varied reinforcing silicon carbide particles from 5% to 20% in 5% intervals and three different level of stirring speeds: 100 rpm, 200 rpm and 500 rpm.

iii. Prepare cast DRMMC specimens for metallographic study, porosity measurement, density determination and mechanical testing according to the ASTM standard dimensions.

iv. Measure the porosity content and density of cast DRMMC specimens at different variables applied.

v. Conduct tensile and fatigue tests at room temperature according to the ASTM standard procedures and analyse the effect of porosity on von Mises stress distribution using finite element method analysis.

1.6 Thesis Layout

The entire idea of the present study is illustrated in Figure 1.2. There were four subsequent chapters written comprehensively in accomplishing the study which comprised literature review and theoretical background, research methodology, results and discussion and conclusion.

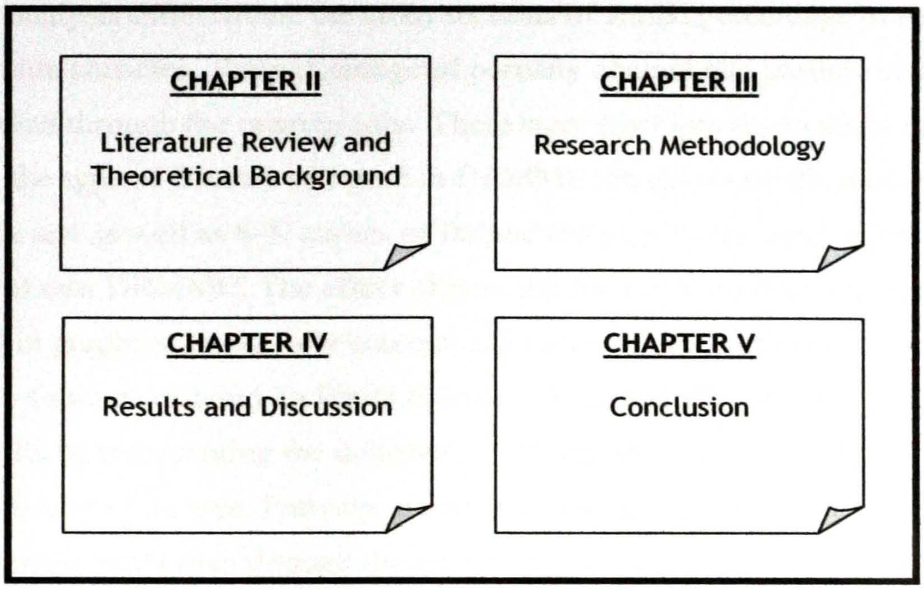

Figure 1.2: Thesis layout

Chapter II discussed the literature review and theoretical background of the current study. In order to understand the various processing methods of DRMMC, significance of stir casting method and porosity formation and the effects of porosity on mechanical properties of cast DRMMCs, it is necessary to review the previous works of established authors as early as 1980s for guidance.

In Chapter III, the experimental procedure provides a precise elaboration on standard of testing applied and specifications of apparatus involved. A complete design of bottom pouring casting rig was available for reference. Metallographic study of fracture surfaces, porosity and particle distribution were performed via scanning electron microscopy, optical microscopy and image analysis. To determine the density of DRMMC, the mass/volume correlation was directly applied. Mechanical testing conducted were the tensile (ASTM B557) and fatigue test (ASTM E466).

Chapter IV presents the research findings and discussion. Graphs were plotted using Excel and statistically analysed. Micrographs from optical microscopy and image analysis differentiate the cross sections of varied percentage of reinforcing silicon carbide particles. The percentage of porosity content and particle distribution were observed through the micrographs. There were fractographs to assist in describing the type of fracture occurred in DRMMC. Stress-strain diagram resulted from tensile test as well as S-N curves of fatigue test signify the mechanical properties of cast DRMMC. The effect of porosity on mechanical properties was interpreted in graphs with porosity content as a function of a particular mechanical property. A simulation based on Finite Element Method (FEM) was supporting the tensile results by representing the distribution of von Mises stress within the analysed specimen cross section area. Porosity presence in DRMMC was clearly verified to affect the tensile properties through the rendered figures.

The final Chapter V summarizes and concludes the present study based on the research findings and discussions.

CHAPTER II

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Introduction

The term "composite" generally refers to a material system which is composed of a discrete constituent (the reinforcement) distributed in a continuous phase (the matrix), and which derives its distinguishing characteristics from the properties of its constituents, from the geometry and architecture of the constituents, and from the properties of the boundaries (interfaces) between different constituents (Surappa, 2003). There are 3 types of matrix material to form composites which are polymer in polymer matrix composite (PMC), metal in metal matrix composite (MMC) and ceramic in ceramic matrix composite (CMC). Among the composites, ceramic matrix composites have much higher temperature resistance. Whereas, polymer matrix composites are limited to low-temperature applications compared to metal matrix composites.

In PMCs, the most commonly used polymer matrix materials is the thermosetting polymers such as phenolics, polyesters, epoxies and polyamides. However, there are also thermoplastic polymers and elastomers matrix materials in PMC system. The reinforcement materials (metals, ceramics, polymers or carbon) are in form of fibers, whiskers, particles and flakes. PMC applications cover the aerospace and military sectors with its advantages such as light weight, corrosion and weather resistance, directional strength, low thermal conductivity and dimensional stability.

In MMC system, the matrix is defined as a metal in all cases, but a pure metal is rarely used as the matrix, it is generally an alloy. The most common metal alloys used as matrix are aluminium (Al), magnesium (Mg), and titanium (Ti). The reinforcement is ceramic material in form of long fibres, short fibres, platelets, particulates and whiskers. Recently, applications of MMC material especially the aluminium composites has been widely accepted in various industrial sectors for its higher specific stiffness, higher operating temperatures, greater wear resistance and possibility to tailor the properties for a specific application.

Ceramic matrix composites combine reinforcing ceramic phases with a ceramic matrix to create materials with new and superior properties. CMCs are designed to provide toughness to the brittle ceramic matrix. Ceramic matrices can be categorised as either oxides or non-oxides. The oxide matrix comprises alumina, silica and mulite whereas the non-oxide matrices are SiC, Si_3N_4 and BC. Mostly encountered CMCs are carbon-carbon, SiC-SiC and carbon-SiC systems. The employments of CMCs are based on their attractive properties which are high temperature stability, high thermal shock resistance, high hardness, high corrosion resistance, light weight and versatility in providing unique engineering solutions

The literature reviews for this research were based on five major elements which involved processing method of DRMMC, significance of stir casting method, formation of porosity in cast DRMMC, the mechanical properties of cast DRMMC, and the effects of porosity on mechanical properties of DRMMC. The processing methods of DRMMC were extracted from, Ejiofor & Reddy (1997), Nguyentat (1997), Clyne (1995), Lloyd (1994) and Ibrahim et. al (1991). Much research work had been done on the field of stir casting method but among the most comprehensive methods was based on Hassan & Gupta (2002), Hashim (1999), Hashim et. al (1999), Moustafa (1997), Clyne (1995), Lloyd (1994) and McCoy et. al (1988) reviews. The works of Hashim et. al (1999), Jiang et. al (1999), Liu & Samuel (1998), Gupta et. al (1997), Murali et. al (1997), Clyne (1996), Chen & Angler (1993), Lewandowski et. al (1989) and Hunt et. al (1987) elaborated more on the porosity formation and classification in cast discontinuous reinforced MMC. Mechanical properties of cast discontinuous reinforced MMC were reviewed from Rawal (2001), Whitehouse (2000), Skolianos (1996), Klimowicz (1994), Ibrahim et. al (1991), Lloyd (1989), and McDanels (1985). In favour of porosity effects on discontinuous reinforced MMC mechanical properties, the reviews were referred to Jung et. al (2000), Whitehouse (2000), Hashim (1999), Chen et. al (1997), Murali et. al (1997), Clyne (1996), Skolianos (1996), Winand (1996), Lewandowski et. al (1989), Hunt et. al (1987), and Jay & Cibula, (1956).

2.2 Processing Methods of Discontinuous Reinforced Metal Matrix Composite (DRMMC)

A wide variety of fabrication methods had been employed for MMC but only a few were selected for DRMMC. These techniques can be conveniently classified into liquid state and solid state processing method. Liquid state processing method comprised the stir casting, spray deposition, *Lanxide* technique and squeeze casting. The costly solid state processing methods compatible for discontinuous reinforced MMC included the powder metallurgy and diffusion bonding.

Osprey Metals (Lloyd, 1994) have been commercialising the spray deposition technique as early as 1974. The processing shown in Figure 2.1 involved melt alloy atomising, and collecting the semisolid droplets on a substrate. Droplet velocities were typically approximately 20-40 m/s. For MMCs, the reinforcement was either already incorporated in the sprayed melt was combined during spraying with the metal, by injection of the reinforcement ingredient material into the sprayed metal droplet stream, or was co-sprayed, that was sprayed at the same time as the matrix onto the substrate. MMC material produced often exhibited inhomogeneous distributions of ceramic particles due to hydrodynamic instabilities in the powder injection or repeated pushing of particles by the advancing solidification front in the liquid or semi-solid layer. Porosity content in the as-sprayed state was typically about 5-10% (Clyne, 1995).

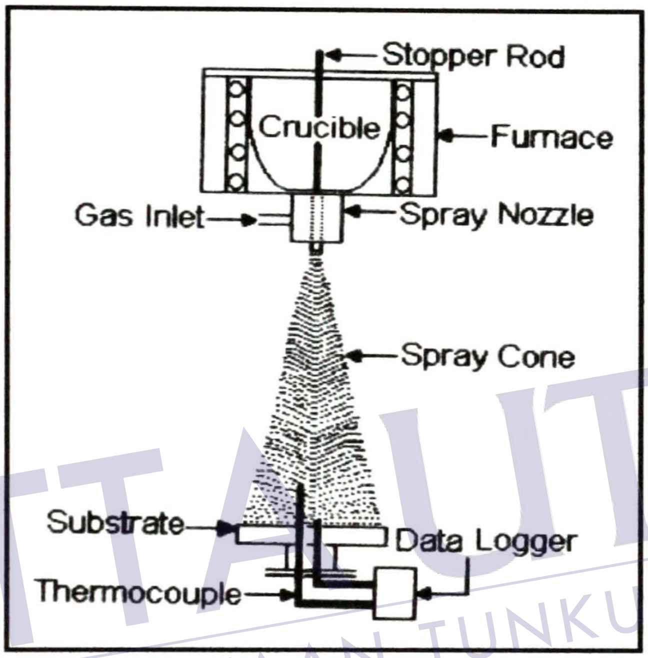

Figure 2.1: Spray deposition technique (Srivastava et. al, 2000)

The *Lanxide* process in Figure 2.2 is a melt oxidation process which involved continuous infiltrations of molten alloy on a ceramic pre-form. The pre-form is normally produced by pressing, slip casting, joining or injection moulding. In air or preferred gas, the molten alloy sliped through the pre-form and chemically reacted with the pre-form material. The final composite phases consisted of the reaction products and remaining matrix material (Ejiofor & Reddy, 1997). Lanxide method produced a dense composite shape and excellent properties of DRMMC, yet it is an expensive processing method.

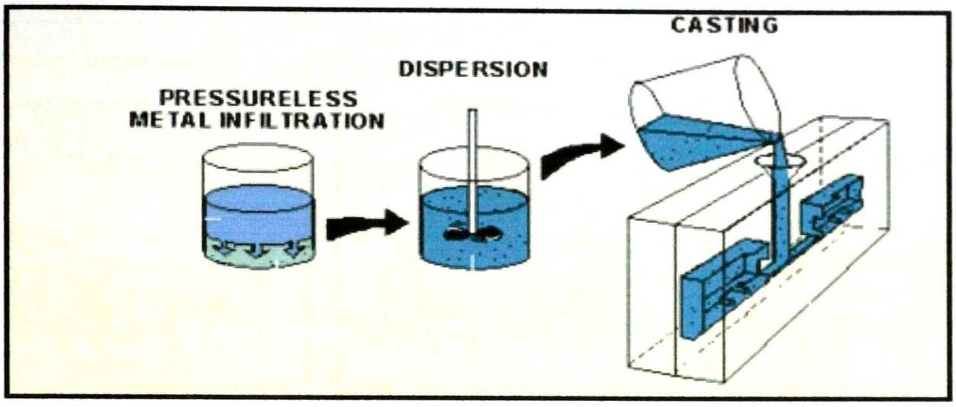

Figure 2.2: Lanxide technique

Squeeze casting is a combination of casting and forging process as shown in Figure 2.3. The molten matrix alloy is poured into the bottom half of the pre-heated die. The upper half closes the die when the matrix alloy starts solidifying. In producing discontinuous reinforced metal matrix composites, porous pre-forms reinforcement material which usually in the form of short fibres or particulates (varies from 10 to 70 vol. %) are infiltrated by molten metal under pressure. However, the pressure applied in squeeze casting is less than that used in forging. Generally, the wetting between pre-form and molten metal is not possible and consequently need to be infiltrated under pressure. A hydraulic ram controlled the pressure applied to the molten metal to avoid damage of the pre-form (Clyne, 1995). The pressure applied tends to favour a strong interfacial bond. However, there were common defects occurred including porosity and variation in the reinforcement material. The stir casting technique will be discussed in the following subtopic 2.3.

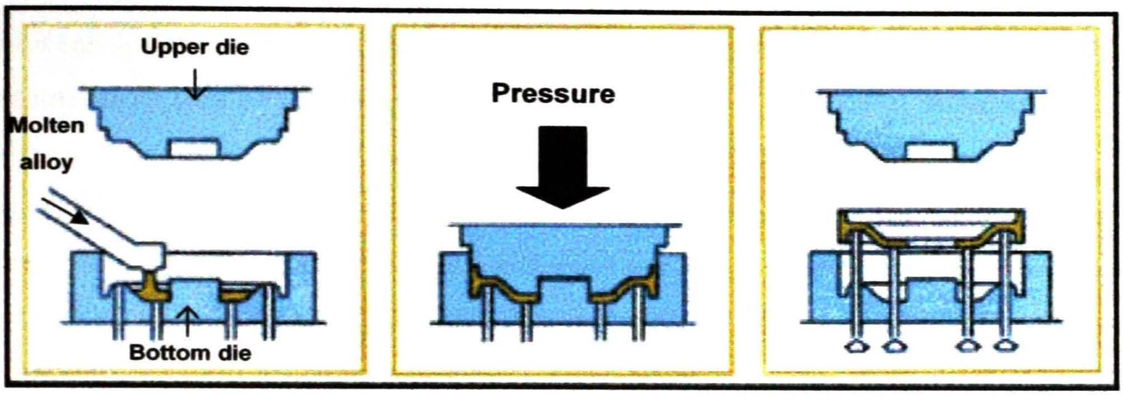

Figure 2.3: Squeeze casting processing method

Powder metallurgy in Figure 2.4 involves the blending of metal matrix powders with reinforcement particulates. It went through cold compaction, canning, evacuation, degassing and a high consolidation stage such as extrusion in achieving approximately 75% density under controlled atmosphere and high temperature. The compaction process is placed in a closed metal cavity. The mixture is consolidated in a short time which benefited the phase transformation control and reduced the possibility of degeneration into coarse microstructure. Therefore, chemical reactions between matrix alloy and reinforcement material are fully avoided and effectively produced optimum mechanical properties of MMC.

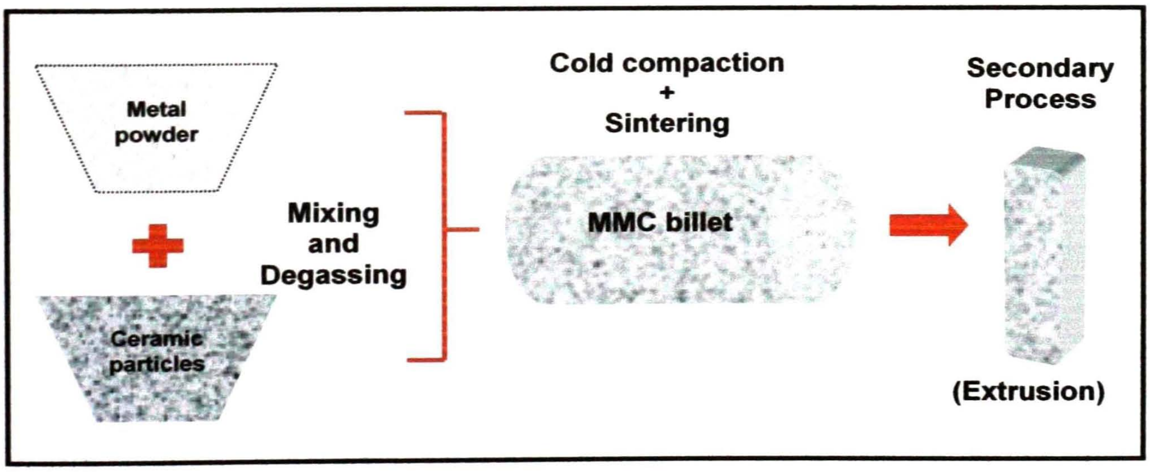

Figure 2.4: Powder metallurgy method

Another solid state processing namely, diffusion bonding, is applicable for platelet reinforced MMC. Referring to Figure 2.5, this bonding technique is based on the atomic diffusion of elements at the joining interface. The platelet diffusion bonding process involved precise laser-cutting of thin platelets to the designed channel. Next, the platelets were arranged and stacked together and diffusion bonded at elevated temperature. The elements diffusion occurred at the platelet interface and result in a metallurgical bond joint. The bonded platelet panels were then formed and machined to the final product (Nguyentat, 1997).

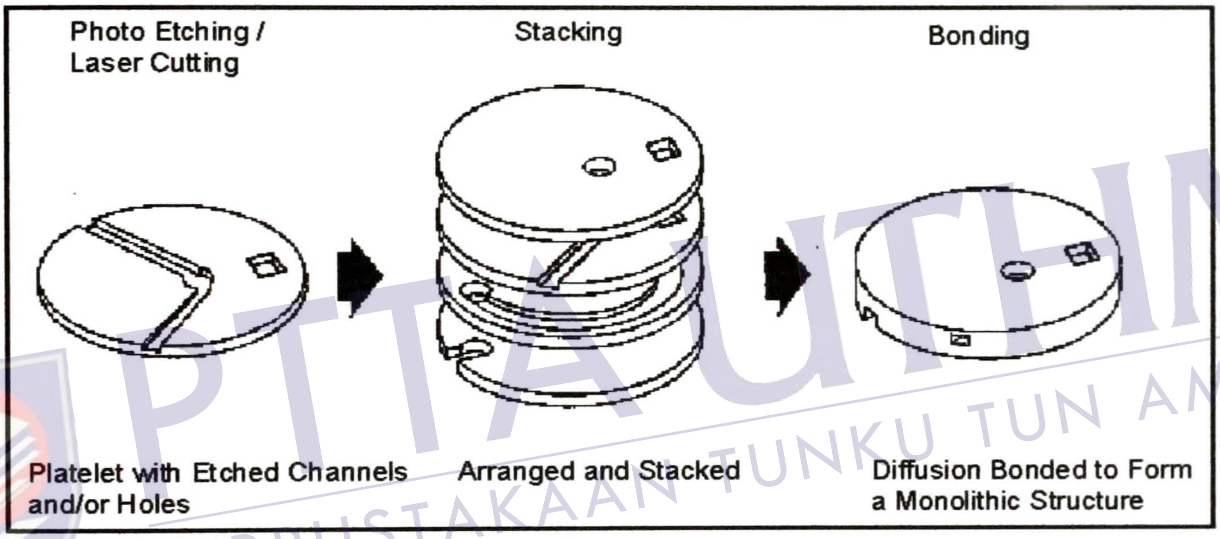

Figure 2.5: Diffussion bonding technique (Nguyentat, 1997).

2.3 Reviews of Stir Casting Method

Economically attractive methods of preparing material and components (Clyne, 1996) could be attained through stir casting method. Available literature indicated that many scientific studies on the aluminium matrix composite reinforced silicon carbide particle occupied the composites which were fabricated through the liquid metal processing specifically the stir casting method (Wu et. al, 2002). Aluminium alloy with silicon as the major alloying element, offered excellent corrosion resistance and could be machined or welded. Besides, their flexibility in component casting and heat treatment, the ability to refine the melt grains and modify the structures, and applications properties make Al-Si alloys more attractive. Moreover, recent reports held that the most preferred of the various matrices and reinforcements studied were Al-alloy matrix and SiC particulates. According to Lindroos & Talvitie (1995), a more improving cost efficiency of mass production techniques was the relatively inexpensive whisker and particulate reinforced aluminium matrix composites. These materials have moderate properties in comparison to continuous reinforced materials. Figure 2.6 illustrates the basic steps of conventional stir casting for fabricating particle reinforced MMC. Conventional stir casting initiates with matrix alloy melting. Then, reinforcement particles were introduced into the melt matrix alloy from top. Mechanical mixing was applied to mix the substances uniformly. Finally, the slurry was being cast into a mould.

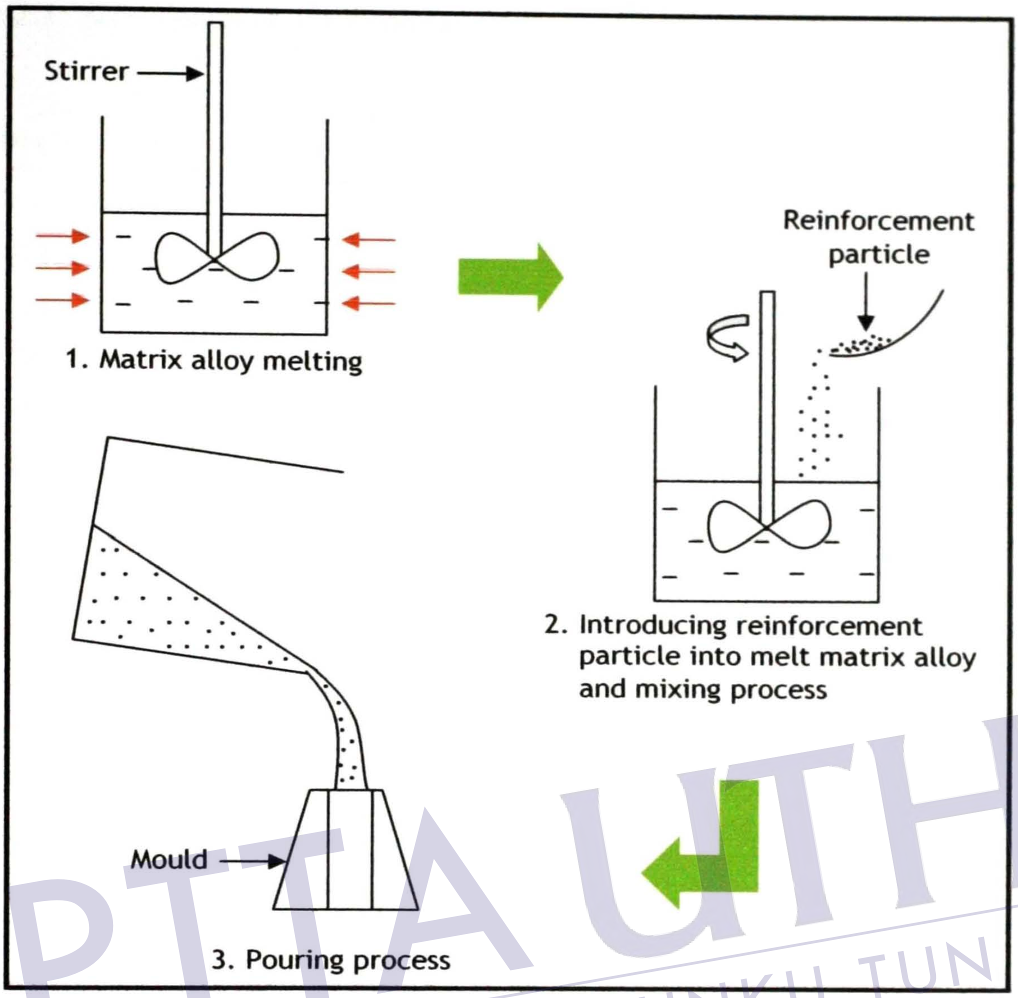

Figure 2.6: Basic steps of conventional stir casting method

From previous works, stir casting varied with the stirring condition employed. Vigorous stirring in vortex method had been pioneering the stir casting method with vortex formation to distribute the reinforcement materials uniformly. Matrix alloy was stirred in fully liquid phase. Lower speed of stirring applied in semisolid phase of matrix alloy designated the compocasting or also known as rheocasting method. The semi-solid state aided incorporation of reinforcement particles as the metal was more viscous. Of all the advantages of processing methods operated in industrial sector, stir casting method continued to be the most popular method because of its appropriateness, ease of operation and total production cost. Table 2.1 showed a comparison of different techniques used in DRMMCs processing.

Table 2.1: A comparison of techniques used in producing DRMMC (Hashim et. al, 1999)

Processing method	**Range of shape and size**	**Metal yield**	**Range of volume fraction**	**Damage to reinforcement**	**Cost**
Stir casting	Wide range of shapes; larger size, up to 500kg.	Very high, > 90%	Up to 0.3	No damage	Least expensive
Squeeze casting	Limited to pre-form shape	Low	Up to 0.45	Severe damage	Quite expensive
Powder metallurgy	Wide range, restricted size	High	-	R/f fracture	Expensive
Spray casting	Limited shape, large size	Medium	0.3 - 0.7	-	Expensive
Lanxide technique	Limited by pre-form shape, restricted size	-	-	-	Expensive

Among the earliest stir casting method was (Surappa & Rohatgi, 1981) limited to coarse reinforcement particles (>50μm) and metal-coated particles. Generally, it is easier to incorporate coarser particles into the melt alloy. Large particles are more accessible to gravity settling (Lloyd & Chamberlain, 1988) while finer particles tend to have poor wettability and increase the melt viscosity and thus making the processing difficult. Reinforcement particles at low volume fraction (<10vol%) were introduced from top of melt alloy and stirred vigorously by a mechanical impeller. However, development of *Dural* process of *Alcan Aluminium Corporation* (Skibo & Schuster, 1989) enabled the usage of uncoated reinforcement particles with finer size range (50 μm>particle size>10 μm). The volume fractions of particle reinforcement were higher as much as 25vol%. In *Dural* process, silicon carbide (SiC) particles and alumina (Al_2O_3) particles are incorporated into molten aluminium producing the *Duralcan* aluminium matrix composite (Ejiofor & Reddy, 1997). Further developments were the *Hydro Aluminum AS* that comparable with *Duralcan* material, and *Comral* (6061 Al matrix alloy reinforced with spherical mixed oxide, $Al_2O_3.SiO_2$) introduced by *Comalco* (Lloyd, 1994). Apparently, the early methods were developing DRMMC through the vortex method.

Optimum properties of particle reinforced MMC were mostly dependant on the uniform distribution of reinforcement particle in matrix alloy, finer size of reinforcement particle, bonding or good wettability between the two main substances (metal matrix and reinforcement materials) and least porosity formation. The uniformity of reinforcement distribution is influenced by the distribution in the liquid as a result of mixing, distribution in the liquid after mixing but before solidification and redistribution as a result of solidification (Lloyd, 1994). Wettability enhancement in cast MMC can be triggered with addition of reactive elements such as Mg and Sr, by heat treating the reinforcement particles at high temperature before the mixing process, by coating the particles with reactive salt coating (such as K_2ZrF_6), or by introducing reactive gases into the molten alloy. Porosity presence in cast MMC reduces the material cross section which consequently acts as stress riser.

Hashim's (1999) work on stir casting route to produce DRMMC focused on the problems emerged in stir cast MMC and few efforts to overcome it. Among the efforts was, discovering the reinforcement pre-heating technique to enhance wettability between matrix alloy and reinforcement material as well as reducing porosity formation in stir cast MMC. Stir casting method has been in commercial use for particulate Al-based composites (Skibo et. al, 1988) and the material produced was suitable for further operations such as extrusion and machining (Hoover, 1991). However, despite the advantages there were difficulties occurred in stir casting as mixing ceramic particles into liquid metals created problems where ceramic particles were not easily wetted by molten metal, (like mercury on a glass surface) the particles would either sank or floated, and the mixture viscosities were very high and shear rate dependent (Lafreniere & Irons, 1990). Hashim's (1999) work supported with Kennedy et. al (1995) observations on liquid processing problems, highlighted the main difficulties occurred during stir casting as follows:

i. porosity in the cast MMC,
ii. achieving a uniform distribution of the reinforcement material in matrix alloy,
iii. wettability between the two main substances and
iv. chemical reactions between the reinforcement material and molten matrix alloy.

Observing cast samples using steel and graphite moulds (Hashim, 1999), and smaller size of ingot, steel mould tended to decrease the porosity content compared to graphite mould as shown in Figure 2.7. Steel mould as well influenced the cooling rate of the ingot. Emadi & Gruzleski (1995) pointed out in Figure 2.8, a faster cooling rate tends to distribute the reinforcement material uniformly and decreased the possibility of porosity formation, as porosity tends to occur among clustering particles (Allison & Jones, 1993). Hence, applying stir casting route as well as pre-heating of reinforcement material and bottom pouring casting (Hassan & Gupta, 2002), (Hashim, 1999), (McCoy et. al, 1988) were significant in attaining a minimum level of porosity, (Ghosh & Ray, 1987). Porosity formation will be discussed in detail in subtopic 2.4.

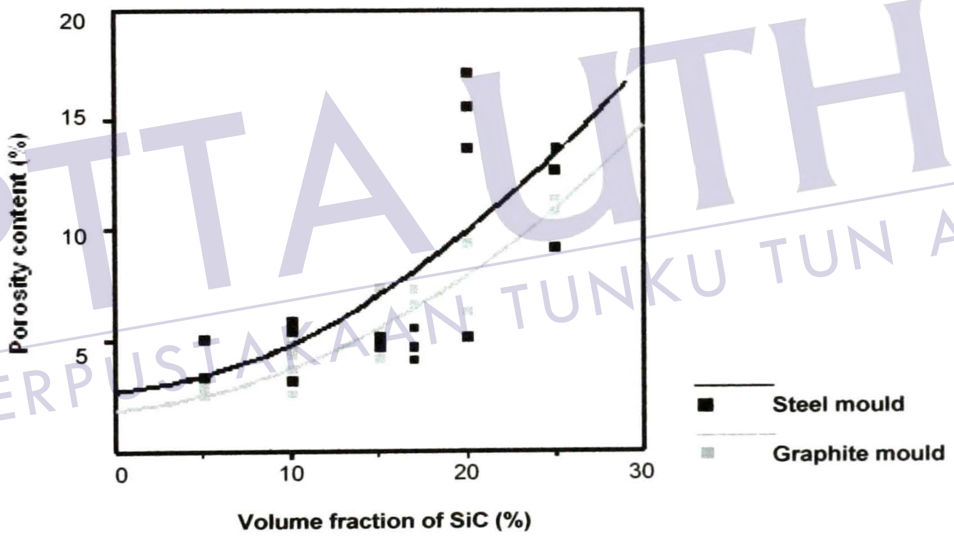

Figure 2.7: Porosity as a function of SiC content (Hashim, 1999)

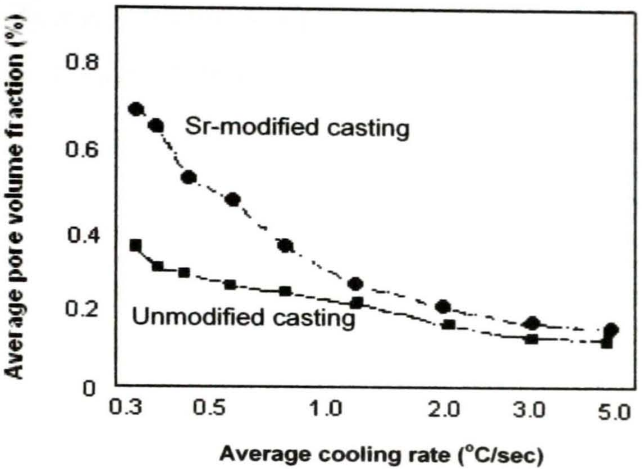

Figure 2.8: Average pore volume fraction as a function of average cooling rate (Emadi & Gruzleski, 1995)

Optimum parameters of stir casting method were necessary in order to obtain an acceptable DRMMC. This was done much by Moustafa (1997) who elaborated the specific parameters on preparing particulate reinforced MMC materials to achieve a uniform distribution of silicon carbide particles in Al-Si alloy. A mixing time of 10-15 minutes range was applied to distribute the particles. The melt temperature during particle addition should be at 80-120°C above the liquidus temperature of the molten alloy to avoid chemical reactions between both main substances. However, if the alloy contains larger amounts of non-reactive elements such as Si, the maximum temperature would be as high as 120°C above the liquidus temperature. Furthermore, the amount of SiC particles and Al_2O_3 particles added into molten matrix alloy was as high as 40wt%. To achieve a homogenous distribution, the diameter of the stirring blades was necessary to be between 30% and 50% of the crucible diameter. High stirring speed introduced gases into the melt and consequently increased porosity formation. In order to avoid particle floatation or settlement before solidification, pouring temperature was between 50-80°C above the liquidus temperature of an alloy. Thus, after completion of the particle addition, the stirring process should be stopped and the mixture temperature was reduced until it reached the pouring temperature. However, two minutes of stirring was required before casting. In addition, the SiC was suggested to be preheated at 750°C for two hours prior to introduction into the mechanically stirred matrix melt and was subsequently cast in permanent moulds.

In general, wettability is defined as the ability of a liquid to spread on a solid surface (Hashim et. al, 1999). In cast DRMMC, wettability refers to the wetting or contact angle less than 90°C for a liquid matrix alloy droplet on a ceramic particle, determined by the sessile drop test (Kennedy et.al, 1995). Poor wettability of reinforcing ceramic particles in matrix alloy was due to gas layers as referred to Zhou (1997). Presence of gas layers made the incorporation of particle in the melt difficult even with vigorous agitation. In order to improve wettability and thus achieving a successful incorporation of reinforcing particle in casting, gas layers need to be broken. Poor wettability tends to promote clustering and inconsistent dispersion of reinforcing particles.

Referring to Clyne & Withers (1993), during the liquidus phase, most metals were reactive toward the reinforcing materials in particular oxides or carbides. A highly reactive metal as aluminium reduced most of the oxides and carbides which were expected to react with the majority of reinforcement material at elevated temperature of ≥850°C. Chemical processes involved were, the oxidation of one element from the matrix and the reduction the reinforcing materials as shown in the following reaction (Zhou, 1997 and Clyne & Withers, 1993):

$$4Al + 3SiC \quad \rightarrow \quad Al_4C_3 + 3Si \tag{2.1}$$

Such reactions result in chemical degradation of the reinforcing materials decreasing mechanical properties of DRMMC, formation of brittle reaction products at the interface, and the release of aluminium carbonate (Al_4C_3) and silicon (Si) elements initially part of the reinforcing material toward the matrix. The reactivity of the matrix alloy toward the reinforcing material could be altered by acting on the matrix composition. For example, the high reactivity of aluminium toward silicon carbide is minimised by saturating the aluminium matrix with Si, preventing most of the deleterious Al_4C_3 formation.

2.4 Mechanical Properties of Cast DRMMC

The widespread of cast DRMMC applications in industrial sector were to replace most of the ferrous metal with its attractive physical and mechanical properties. DRMMC was noted to weigh less than ferrous metal and yet able to provide compatible mechanical properties. Based on observation of Tan et. al (2001), the strength of composite was mainly determined by the balance between reinforcing particles sharing load. However, occurrence of porosity as discontinuities in cast DRMMC had interrupted the balance and thus, reduced its mechanical properties.

McDanels's (1985) work emphasized the elastic modulus of composites was found to be isotropic and to be controlled solely by the volume percentage of reinforcement present. The ductility, yield stress and ultimate tensile strength were mainly controlled by the matrix alloy and temper condition. However, in particular DRMMC, the mechanical properties (at room temperature) were influenced by large size of particles and clusters of the reinforcement; locations which prone to failure in the composites due to high stress concentration (Cocomazzi, 1999). Reinforcement particles (for example: silicon carbide particle) appeared to have a significant stress-raising effect on the formation of slip bands and cracks as there were micro pores forming during solidification in the reinforced alloys unlike the un-reinforced. These micropores were preferred nucleation sites for fatigue cracks. The following Table 2.2 indicates several mechanical properties of cast discontinuous reinforced DRMMCs.

Table 2.2: Some mechanical properties of aluminium alloy and particle reinforced Al-DRMMCs

Reference	Material	Yield stress σ_Y (MPa)	Tensile strength σ_{TS} (MPa)	Elongation (%)	Young's Modulus E (GPa)
Lloyd (1989)	A356	175	280	10	71
	A356/SiC/15p	270	295	1.5	95
Duralcan in Ibrahim et. al (1991)	A356	200	276	6.0	75
	A356/SiC/10p	283	303	0.6	81
	A356/SiC/15p	324	331	0.3	90
	A356/SiC/20p	331	352	0.4	97
Klimowicz (1994)	A356	194	298	11.9	75.1
	359/SiC/20p	338	358	0.4	98.5
Skolianos (1996)	Al2024	85.1	103.0	5.2	6.5
	Al2024/SiC/4p	101.2	114.2	5.0	9.8
	Al2024/SiC/12p	118.0	123.0	5.0	18.2
	Al2024/SiC/25p	143.2	161.0	2.1	22.0
Rawal (2001)	Al6092/SiC/17.5p	406.5	461.6	-	100
	Al/SiC/63p	-	253	-	220

The mechanical properties mentioned above highlight such as yield strength, tensile strength and Young's modulus increased with the increasing of reinforcement particles added. Among the un-reinforced A356 alloy, Duralcan produced the highest yield strength whereas; referring to result from Klimowicz (1994) works, the tensile strength and elongation was higher compared to the Duralcan and Lloyd (1989). Referring to 15% and 20% SiC_p reinforced A356, Duralcan DRMMCs properties, were superior in term of yield strength, and tensile strength. However, the toughest DRMMC properties were referred to Rawal (2001) works on space applications DRMMC.

The fatigue behaviour of cast DRMMC was significantly related to its ductility and strengthening mechanism (Whitehouse, 2000). Strengthening mechanism in DRMMC was related to the volume fraction of reinforcing particle in the matrix alloy. Referring to Table 2.3, as the reinforcing particle increased and, the fatigue strength of DRMMC was enhanced while the ductility was decreased. Figure 2.9 and 2.10 comparing the un-reinforced alloy and DRMMC which pointed out the

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