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

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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 1×10^7 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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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.

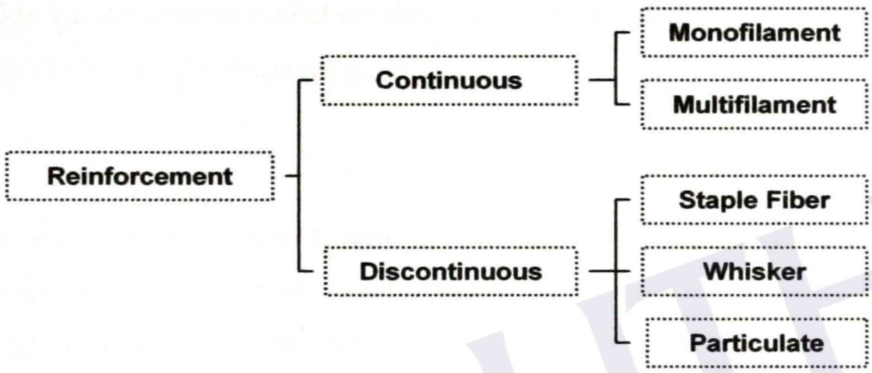

Figure 1.1: Forms of reinforcement

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.

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